82   04   16   016

the clock equations given in Table 2. Generally, residuals were not corrected

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    In August 1980, three experimental geodetic Global Positioning System
Receivers were deployed in the Washington, D. C. area by the Naval Surface
Weapons Center, the International Business Machines Corporation and Shell
Canada Limited. Analysis of five to six hours of Doppler observations
distributed among four satellites yielded relative position coordinates
on a 28 km baseline which were repeatable to 30 cm in height, 70 cm in the
East directions and to 10 cm in the North directions. Results obtained

for a receiver equipped with an oscillator having poorer stability degraded to 50 cm to 1.5 meters. The results confirm simulations that Doppler observations made with the geodetic receiver under development will yield decimeter accuracy in relative position in one to three hours. Since the experimental receivers required about a minute to sequence between satellites, tests could not be performed to test cm precision in relative station positioning which can be obtained by comparing phase observations between satellites with receivers under development.
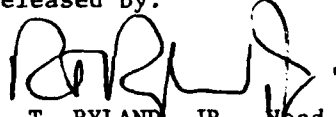
FOREWORD

This is one in a series of reports on the development of a geodetic
receiver for application with the NAVSTAR Global Positioning System. The
objective is to develop a receiver capable of determining relative positions
of sites to cm accuracy in an hour or two and absolute positions of sites
to an accuracy of a meter in a day. The development is sponsored by the
Defense Mapping Agency, the National Geodetic Survey, and the United States
Geological Survey.

Tests of three experimental geodetic receivers were coordinated by
Dr. Alan Evans of the Naval Surface Weapons Center, Dr. Francis Byrne of the
International Business Machines Corporation and Dr. Alex Hittel and Norman
Beck of Shell Canada Limited. These coordinators and their associates
provided the information necessary to conduct the analysis discussed in this
report. Brian Tallman and Hank Heuerman of the Defense Mapping Agency
Hydrographic/Topographic Center provided terrestrial survey data and meteorology
and other equipment used in the tests. The close cooperation of Al Evans is
particularly acknowledged as well as the careful efficient work of Linda T. Lynch
who assisted in the development and operation of computer programs used in the
analysis. The experimental receiver deployed by NSWC was developed by
Bruce Hermann of the Strategic Systems Department and assembled, tested and
operated by Ted Saffos, Ralph Dickerson, and Glenn Bowen of the Electronics
Systems Department.

Released by:

R. T. RYLAND, JR., Head
Strategic Systems Department

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CONTENTS

BACKGROUND

Observations of Navy Navigation Satellites have been used since 1963 to determine geodetic positions of thousands of sites around the world to one meter accuracy (Anderle, 1976). Observations at each site are typically made for a period of time of one to five days. A Department of Defense Joint Project Office chaired by the U. S. Air Force is developing the NAVSTAR Global Positioning System (GPS) which is intended to supplant the Navy system for navigation. (An extensive discussion of the system is given in papers published in NAVIGATION on the "Global Positioning System" which have been reprinted by the Institute of Navigation.) Therefore the Naval Surface Weapons Center initiated studies to determine the optimum use of the GPS system for geodetic operations. The in-house studies were later sponsored by the Defense Mapping Agency and are now conducted in response to requirements of a joint agency group which includes the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration, and the United States Geological Survey as well.

Simulations showed that equipment being developed by the GPS Joint Project Office for navigation applications would be capable of providing absolute positions to one m accuracy in about a day and relative positions to a few decimeters accuracy in a few hours (Fell, 1980). These results, which were based on range measurements obtained by correlating the pseudo-random noise sequence transmitted by the satellite with a similar sequence generated by the receiver, were in themselves an improvement over the capability of the current NAVSAT system, particularly because the 20,000 km altitude of the GPS satellites would permit the determination of relative positions over considerably longer baselines than could be used with the 1000 km altitude NAVSAT satellites. However, the range measurements can be made to only about one m precision while phase or Doppler measurements on the reconstructed GPS carrier signals can be made to cm precision. Since the phase one GPS receivers used Doppler measurements at only one frequency, the NSWC effort was concentrated on exploiting Doppler measurements on two frequencies. Absolute positioning accuracy would still be limited by the uncertainty in the GPS ephemeris, but relative positioning accuracy could be improved with increased measurement precision, and any future improvements in ephemeris accuracy could be exploited.

The Stanford Telecommunications Incorporated (STI) constructed a receiver to NSWC specifications which required phase and Doppler measurements to two and three mm precision at 1575 and 1228 Mhz, respectively and range measurements at 1575 Mhz to one m precision. NSWC added a cesium oscillator, time and Doppler counters, placed the receiver under computer control and assembled the system with test equipment in a small van. A second STI receiver has also been obtained which has similar measurement capabilities to the first model, except that range measurements are made at two frequencies. This model was also procured by International Business Machines Corporation and Shell Canada Limited who independently assembled the other two systems used in the tests discussed in this report. Tests previously showed that the equipment is capable of the specified sub-centimeter measurement precision, although the measurement precision is masked by oscillator instability for

integration times of the order of a minute or more (Hermann, 1981, Evans et al, 1981). The effects of oscillator stability on the error in the relative positions of two sites can be reduced to a negligible level if the two sites observed two or more satellites during a sufficiently small interval of time. Several measurement and computational techniques are available to exploit quasi-simultaneous observations of two or more satellites (MacDoran, 1970, Bossler et al, 1980, Counselman and Shapiro, in press). However, the receivers used in these tests required about a minute to acquire a new satellite, which resulted in too long a time interval between observations of pairs of satellites to permit successful ambiguity resolution in view of the stability characteristics of the Cesium oscillators used in this test (Anderle, 1981).

DATA ACQUISITION

The Cesium oscillators used by each of the receivers were sent to the U. S. Naval Observatory for a determination of their stability characteristics. Due to scheduling constraints on the use of the receivers, the stability characteristics of the oscillators could not be determined reliably for sample times longer than five minutes, although values for times as long as several hours would have been useful for the Doppler application of the system. Dr. Ken Putkovich provided the following data from the laboratory tests:

Sample Time	Shell FTS 134	IBM 653	NSWC HP 2002-80-1660
1 sec	1.03×10^{-11}	6.49×10^{-12}	-
3	1.08×10^{-11}	7.50×10^{-12}	-
10	6.1×10^{-12}	3.29×10^{-12}	$2. \times 10^{-12}$
30	3.54×10^{-12}	1.83×10^{-12}	$1. \times 10^{-12}$
100	2.3×10^{-12}	1.52×10^{-12}	0.5×10^{-12}
300	1.1×10^{-12}	1.45×10^{-12}	4.3×10^{-13}

These data are shown in Figure 1 along with the Allan variance for the satellite Rubidium oscillators obtained in pre-launch tests and that of a Rubidium oscillator for which simulations have been performed (Anderle, 1981). Note that the performance of the Cesium oscillators is significantly worse than that of the Rubidium oscillator for which the simulations were performed. This difference was to be expected since the Cesium oscillators were tuned to optimize their stability characteristics at considerably longer averaging times than those at which the tests were performed. It should also be borne in mind that the field performance of the oscillators could be worse than that encountered in the laboratory conditions of the tests.

The GPS observational data discussed in this report were acquired from day 262 (18 September) to day 277 (3 October) of 1980. Initially, all three receivers were at the IBM location in Gaithersburg, Maryland. On day 266,

ALLAN VARIANCE

$C \times \tau \times \dfrac{\Delta f}{f}$ (cm)

NDS R_b (PRE LAUNCH)

IBM C_e

SHELL C_e

NSWC C_e

EFRATOM R_b

$\dfrac{\Delta f}{f}$

10^{-11}

10^{-12}

10^{-13}
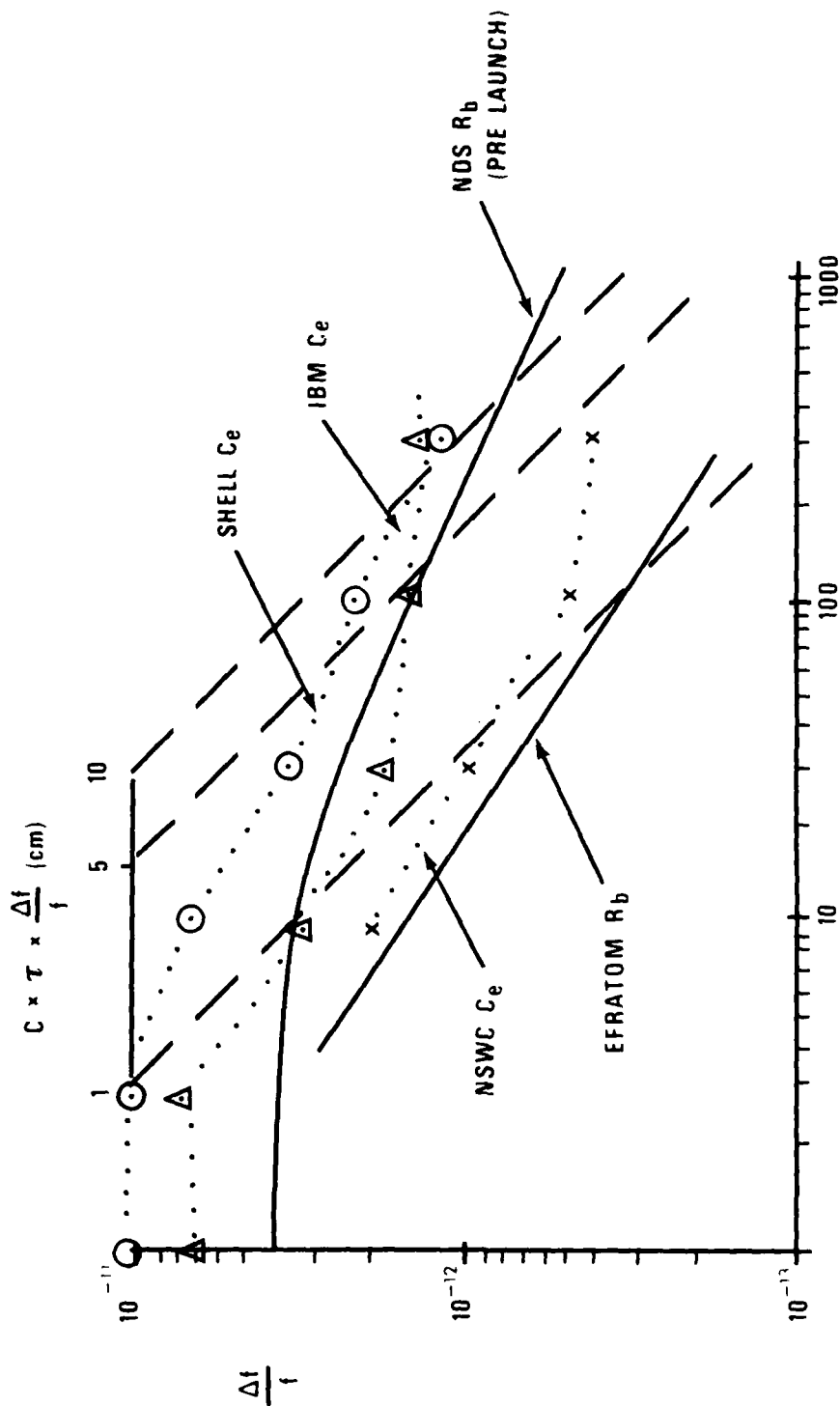
1   5   10

10   100   1000

TIME τ (SEC)

FIGURE 1

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the Shell equipment was moved to Upper Marlboro and the NSWC equipment was moved to Arlington, to form a triangle about 25 to 60 km on a side as shown in Figure 2. Finally, on day 276, the Shell equipment was moved to the NSWC location in Arlington. The antenna positions were surveyed with respect to the Geodimeter traverse in the area by the Defense Mapping Agency Hydrographic Topographic Center and the resulting coordinates were transformed to the Department of Defense World Geodetic System 1972. The coordinates provided by Hank Heuerman of DMA/HTC are given in Table 1.

Data were acquired as planned throughout the period from day 263 to day 277 with the following exceptions:

1. On day 264 and 265 (Saturday and Sunday), only NSWC recorded data.

2. On day 267, Shell did not collect data because of an equipment connector problem.

3. On days 273 and 274, IBM did not record the second pass of satellites 6 and 9.

A different satellite observing schedule was planned for most days during the test period. The switching schedule among satellites varied from three minutes to several hours. The sequence of the satellites specified in the switching varied on different days, and on some days differed for one of the receivers. During the analysis of Doppler data discussed in this report, the data taken at the three minute switching interval were discarded.

DATA PREPROCESSING

A common data format was agreed upon by the three agencies participating in this experiment. The Doppler data was converted to accumulated range differences, and the results were exchanged among the agencies in the specified format. However, the method of recording and converting data varied among the participants so that the quantities given had different physical meanings. The NSWC Doppler counts were measured and time-tagged according to the ground oscillator time scale. For purposes of this report, these observations were converted from the original measurements to accumulated range differences and time-tagged according to the ground clock. The Shell and IBM receivers recorded Doppler at the times of receipt of the pseudo-range signals and time-tagged the data with GPS time of signal emission. (The Shell Doppler data were time-tagged six seconds later than the actual time of emission.) IBM calculated the range difference increments at the times of receipt of the signal from the formula:

$$\angle R = \lambda \; (N-8125) \; x \; (6 + \rho/c)$$

where
λ is the wave-length of the carrier signal
N is the Doppler count difference
ρ is the pseudo-range
c is the velocity of light
8125 is the offset of the receiver reference frequency above the normal carrier frequency.

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RECEIVER LOCATIONS

LONGITUDE

FIGURE 2

LATITUDE

SHELL
38.1 KM
52.0 KM
IBM
28.4 KM
NSWC

284   283   282

40   39   38

5
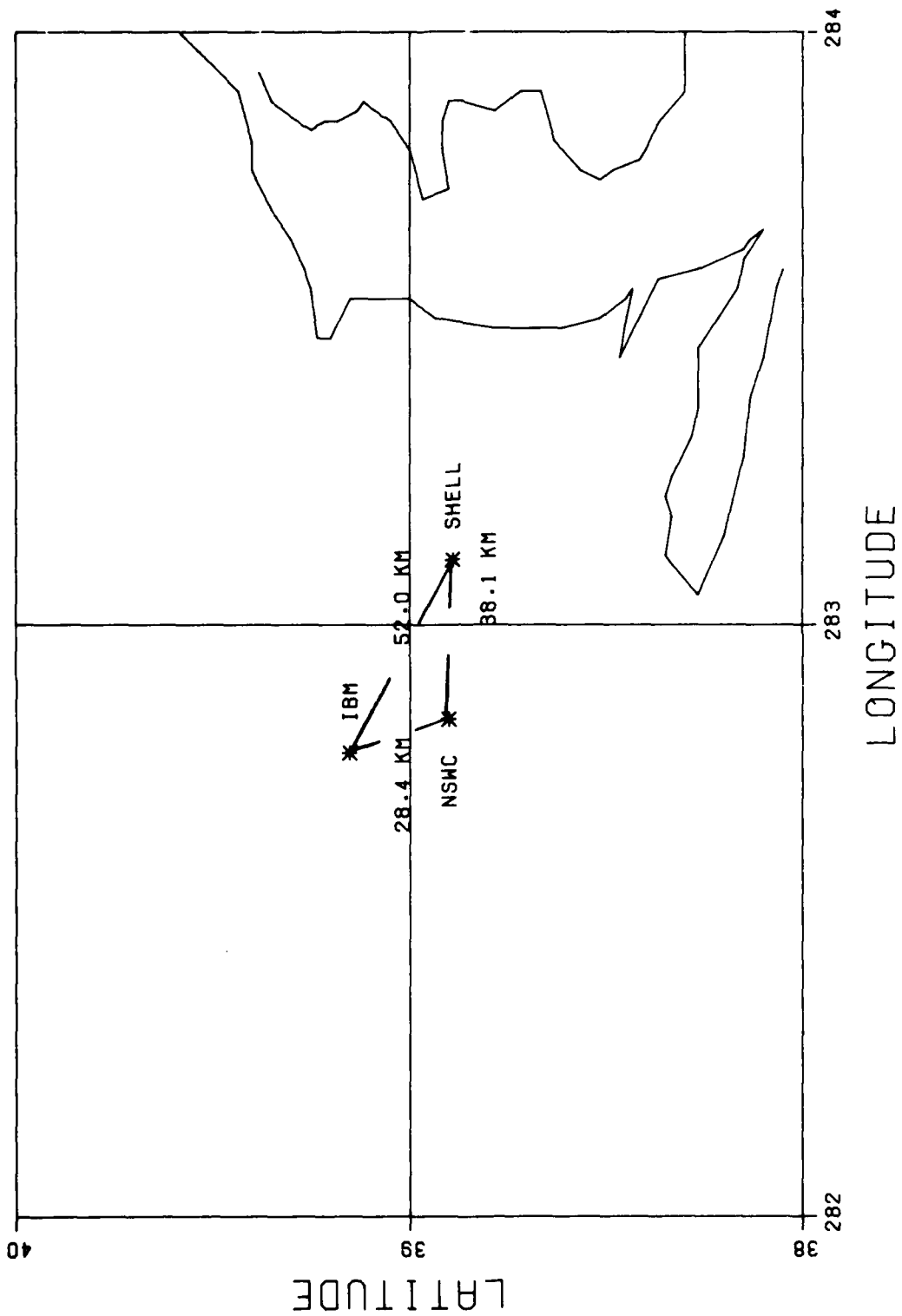
Table 1

RECEIVER POSITIONS

DoD WGS-72 REFERENCE SYSTEM

Equipment	Time Period Days, 1981	Location	Latitude	Longitude	Height
IBM	262-267	Gaithersburg	39°.1528868	282°.7842276	.11473 km
Shell	262-267.5	Gaithersburg	39.1528411	282.7841627	.11443
	267.5-276.5	Upper Marlboro	38.8900587	283.2810772	.01899
	276.5-277	Arlington	Same Antenna as NSWC		
NSWC	262-267.5	Gaithersburg	39.1528927	282.7842495	.11470
	267.5-277	Arlington	38.9012578	282.8415589	.10503

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This is the range difference which would be read out at six second intervals on the ground station clock. IBM accumulated these range differences and time-tagged them with the hand-over word (GPS time of week in units of six seconds). At NSWC, these accumulated range differences were re-tagged with ground receiver time calculated by adding ρ/c to the time of day corresponding to the hand-over word. Shell did not apply the ρ/c correction in calculating the accumulated ranges, so this correction was applied at NSWC. (Since the Shell receiver reference frequency is offset 8125 below the nominal carrier frequency, the sign of the correction is reversed with respect to the IBM formula.) The Shell data were time-tagged using the same procedure applied to the IBM data.

The net result of this pre-processing was that the accumulated range difference data for the three receivers were referred to their respective ground clocks; the NSWC data were at integer six second intervals while the IBM and Shell data were at intervals which differed from six seconds by the amount of the travel time of the signal. Therefore it was necessary to determine the level of time synchronization among the receivers, and between the receiver clocks and the time used in generating the ephemerides to be used in the data analysis. The ephemerides were generated in GPS time; offsets between the time of emission of the hand-over words and GPS time are broadcast in the satellite message which was recorded by the receivers. The offsets between each satellite and each receiver were calculated from the pseudo-range measurements and have been plotted in Appendix A. (Calculations for the NSWC receiver were only performed for satellite 9.) Results of linear and quadratic least squares fits to these corrections are summarized and compared with approximate linear fits to the broadcast offsets with respect to GPS time in Table 2. The NSWC receiver differed from GPS time by about 10μ sec while the IBM and Shell receivers differed from GPS time by about -25μ sec. Since 10μ sec corresponds to about one cm in satellite position and since we are concerned with differences in satellite position with respect to time, it was not deemed necessary to correct the observation times for these small offsets.

Portions of the equations of condition were formed for the integrated range difference observations made at one minute intervals using the station coordinates given in Table 1 and using ephemerides fit to seven days of observations made by the four GPS monitor stations in California, Alaska, Hawaii and Guam. (For part of the test, the rectangular coordinates for the NSWC receiver were offset from those corresponding to the geodetic coordinates given in Table 1 by the equivalent of 10 m in latitude, to obtain additional validation data for the computer program used.)

Relativistic corrections were not made to the observations despite the fact that the corrections were made to observations from the monitor stations which were used to determine the orbits of the satellites. This omission has a negligible effect on the computation of the relative position of the receivers due to the short base lines involved. During the formation of the normal equations, the residuals were corrected for satellite frequency offsets of 9600, 2500, 10500, and -20 ns/day for satellites 5, 6, 8 and 9, respectively. These corrections were obtained from results obtained in the ephemeris computations, but equivalent values could have been obtained from

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Table 2a

Clock Calibration (Linear Solutions)

Epoch of Clock Equation on Day 260

Clock error $= a_o + a_1 t + a_2 t^2$

Satellite	Receiver	How-Word with Respect to Receivers		GPS Time with Respect to Receivers	
		a_o (ms)	a_1 (ms/day)	a_o (ms)	a_1 (ms/day)
5	IBM	.094	.0094	−.025	−.0007
	Shell	.092	.0098	−.027	−.0003
6	IBM	−.323	.0024	−.024	−.0002
	Shell	−.324	.0027	−.025	.0001
8	IBM	.397	.0104	−.032	.0000
	Shell	.396	.0107	−.033	.0003
9	IBM	.348	−.0001	−.023	−.0001
	Shell	.347	.0002	−.024	.0002
	NSWC	.383	.0001	.012	.0001

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Table 2b (Quadratic Solutions)

Satellite	Receiver	How-Word with Respect to Receivers			Residuals
		a_o(ms)	a_1(ms/day)	a_1(ms/day^2)	(μs)
5	IBM	.095	.0092	.00002	.058
	Shell	.095	.0091	.00004	.106
6	IBM	-.323	.0024	.00000	.073
	Shell	-.323	.0023	.00002	.185
8	IBM	.397	.0103	.00000	.076
	Shell	.397	.0102	.00003	.074
9	IBM	.349	-.0004	.00002	.117
	Shell	.349	-.0005	.00004	.117
	NSWC	.383	-.0001	.00001	.047

the clock equations given in Table 2. Generally, residuals were not corrected for station frequency offsets although Table 2 shows the frequency of the IBM oscillator to be about 250 ns/day below NSWC and Shell to be about 150 ns/day above NSWC. While these offsets are somewhat above the 100 ns/day uncertainty assigned to the a-priori values, tests of the 400 ns/day offset between the IBM and Shell oscillators affected relative station positions by only about 10 percent of the scatter in the results. The equations of condition included the partial derivatives of integrated range difference with respect to corrections to the rectangular coordinates of the station and with respect to the scale factor for the Hopfield refraction model. However, the refraction correction to the residual and the partial derivative was erroneous due to a programming error; the erroneous correction was removed and it and the partial derivative were replaced by 2.54/cos (Zenith Angle), in meters, in the program used to form and solve normal equations.

First and second differences of the residuals were obtained and first and second differences of differences in residuals for pairs of stations were also obtained. It was evident from either set of differences for satellites 5, 6 and 8 that the NSWC receiver occasionally skipped a cycle count at the 1575 Mhz frequency. The effect on the vacuum range is a 48 cm discontinuity in the first differences which was obvious in the second differences which were three to five cm normally. (The three to five cm corresponds to the effects of short term oscillator instability.) Therefore a program was written which corrected subsequent residuals by 48 cm whenever a second difference exceeding 25 cm was encountered. It was not expected that this procedure would be reliable for satellite 9 data because the short term stability of the Cesium clock on satellite 9 is poorer than that of the Rubidium clocks on the other satellites. Any missed cycles could have been detected by processing the six second integrated range difference data; but to avoid processing this large quantity of data, the second differences of the differences between IBM and NSWC residuals were inspected by eye. These second differences were three to five cm because the satellite clock variations do not contribute to them. No discontinuities were noted, so no corrections were made for satellite 9. No such problems were noted in the IBM data. The second differences of the Shell data were frequently significantly higher than those for the other two receivers, leading to the suspicion that counts were also missed by this receiver. However, samples of six second data showed that counts were not missed at the suspected points, so the higher level of noise was attributed to the poorer short term stability of the Shell oscillator (Figure 1). Therefore no automatic adjustments were made to the Shell data. However, manual editing of data points was performed on data from all three receivers to delete observations which were determined to be erroneous because of excessive second differences. The manual editing of the NSWC data was due either to errors in the pre-processing program or to missed cycles for satellite 9 observations which were not subject to automatic error detection.

Since the principal objective of the analysis was to determine the relative coordinates of the receivers, the data for each pair of receivers was compared and only data observed at the same time (within the propagation delay) were passed to the program used to form and solve normal equations. Schematics of the observations remaining during 24 hour time periods starting at 1200 UTC are given in Appendix B for each pair of stations. A symbol is

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plotted for each tenth point on the charts, and each time the integrated count is interrupted, the number of observations in the segment is printed above the symbol. Since the number of points are overprinted in many cases, a summary of the pass lengths is given in Appendix B, Table 1. The geometry of the passes is shown on the maps in Appendix B for the NSWC/IBM observations for each day and for the NSWC/Shell data for day 276, 277 (when the two receivers used the same oscillator and antenna). The satellite ground tracks are plotted at 10 minute intervals; the time in minutes is printed to the right of the point and the satellite is indicated by the numbers 1 through 4, referring to satellites 5, 6, 8 and 9 in that order.

DOPPLER SOLUTIONS

Normal equations were formed for the positions of each pair of receivers, for range biases for each sequence of integrated range differences from a station to a satellite, for linear clock equations for each satellite and receiver, for refraction scaling parameters for each point and pass, and for six orbit bias parameters for each satellite. The orbit bias was represented as a 12 hour periodic error in the along track, radial and normal position of each satellite. The minimum matrix size carried during the processing is summarized below:

Rectangular coordinates of first station	3
Rectangular coordinates of second station	3
Refraction point scaling parameter	2
Refraction pass scaling parameter	1
Range bias parameter per pass (2 stations, 4 satellites)	8
Clock equations per pass	
Epoch and frequency, 2 stations	4
Epoch and frequency, 4 satellites	8
Orbit bias per pass (6 parameters; 4 satellites)	24
TOTAL	53

Upon completion of a pass, the matrix, right hand side and predicted residuals are adjusted to account for the elimination of the appropriate parameter, and the space in the matrix reused for the next pass parameter. A "pass" can be defined differently for different parameters. The range bias parameter is re-determined each time the Doppler count from a given station on a given satellite is interrupted. For the computations reported here, the refraction pass and orbit bias pass extended throughout the 1000 minute maximum time span used for each solution for station coordinates. Three cases were run for the clock biases. In case A, the clock biases extended throughout the 1000 minute solution. In case B, the clock biases extended for the same duration as the range biases. Finally, in case C, a maximum span of 60 minutes was set for each clock equation. The presence of both a range bias and clock epoch parameters in the solution produces a singularity which was resolved by assigning a large uncertainty to the a-priori clock epoch parameters. Other uncertainties assigned to a-priori values of parameters were:

Each coordinate of reference station:	10 meters
Refraction point parameter	: 1%
Refraction pass parameter	: 5%
Satellite frequency	: 300 ns/day
Reference station frequency	: .01 ns/day
Second station frequency	: 100 ns/day
Orbit parameters	: 5 m radially
	10 m tangentially
	15 m normal

The observations were assigned a random error of 3 cm.

Solutions for station coordinates and frequencies based on the NSWC/IBM data are given in Appendix C, Tables 1-3 for the three representations of the frequency parameters. Case A (Appendix C, Table 1) is the statistically strongest solution since the frequency parameters for each satellite and receiver extends throughout the 1000 minute data span. However, the statistical modeling of the oscillator error is poor in this solution since the oscillator variation shown in Figure 1 generates errors which exceed the 3 cm random error assigned to the observations. Cases B and C (Appendix C, Tables 2 and 3) introduce successively more frequency parameters, weakening the solutions, but reducing the discrepancy between the extent of oscillator variation and the size of the random error. Only the satellite orbit corrections obtained in solution A are listed in this report (Appendix C, Table 4). The size of the corrections to frequencies, absolute station coordinates of the IBM receiver, and to orbit parameters as well as the weighted residuals are exceptionally large for day 270. They are similarly large for solutions based on other station pairs to be discussed below. An orbit adjust to satellite 9 was made on day 269; it is believed that the excessive corrections and residuals for day 270 are due to difficulty in fitting the reference orbit through the discontinuity produced by the thrust. The relative station coordinates do not appear to be unusually disturbed for this day, since even a relatively large orbit error will not affect relative positions of closely spaced stations at the level of accuracy of the solutions reported here. Solutions for days 268, 269 and 270 were recomputed without the data for satellite 9. While the parameter corrections and residuals were reduced to reasonable levels, the changes in relative station positions were not significant compared to the scatter in either set of solutions (the set with or the set without satellite 9). Corresponding solutions for the Shell/NSWC stations are given in Appendix C, Tables 5-8 and for the IBM/Shell pair in Appendix C, Tables 9-12. The comments made above for the NSWC/IBM solutions apply to the day 270 solution given in Appendix A, Tables 5-12. In addition, residuals for day 263 are large for a reason which has not been identified.

The mean relative positions and standard error of the mean relative positions are given in Table 3. Generally, the discrepancies from the surveyed positions are not significant compared to standard error of the mean computed from the scatter of the individual 1000 minute solutions. Exceptions are the height coordinate obtained in the NSWC/IBM case A and probably the height coordinates in the IBM/Shell solutions. NSWC/Shell tests with the same oscillator and antenna seem to rule out any sources for the biases other than oscillator or antenna. The scatter of the 1000 minute solutions with respect to the mean of all solutions in a case are given under the column "Standard Deviations" in Table 4. The consistency in the NSWC/IBM Case A results is 30 cm in height, 70 cm East and 10 cm North. The maximum number of data points in any of these solutions corresponds to about 725 minutes of sequential tracking. This quantity of data can be obtained in three hours with the rapidly sequencing receiver now being constructed. The results are reasonably consistent with those shown in the table for simulations, particularly considering the discrepancy in stability between the test and simulated oscillators.

The consistency of results for the other frequency representations for the NSWC/IBM data degrades to 50 cm to 2 m. In all cases, the consistency of the solutions is about a factor of five worse than the standard error

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of the solutions obtained from the covariance matrix which considered only the a-priori data uncertainties and the pass geometry. (The standard errors are also given in Table 4.) The factor of five would be reduced if the standard errors were scaled by the weighted residuals as is customary. However, the excess of these weighted residuals over unity is due almost entirely to the orbit error on day 270, which did not materially affect the scatter in relative station positions. The factor of five is not unreasonable in view of the Allan variance of the IBM oscillator shown in Figure 1.

The scatter of the Case A solutions involving the Shell data is 1 to 1.5 m in height and East and 50 cm in the North direction. Results with weaker oscillator representations are progressively worse. The standard deviations of the Shell data are about 10 times the standard errors, but the weighted residuals for Shell are typically two, even for the best results. The larger residuals probably reflect the larger short period noise of the Shell oscillator as shown in Figure 1. Since the oscillator stability at the longest period shown is slightly better for Shell than for the IBM receiver, the explanation for the larger standard deviations for Shell is not obvious. Possibilities include (1) unknown oscillator stabilities at longer periods which are more critical to the results, (2) the longer base line between the Upper Marlboro location and the other locations, or (3) something unique about the radio frequency environment at Upper Marlboro where most of the Shell data were acquired. It is not believed that the base line length is a significant factor. Oscillator stability is the most likely cause of the large standard deviations.

The Shell/NSWC data on day 276 were obtained in Arlington using the same antenna and oscillator. The strongest solution, given in Appendix C, Table 5 for the day 276 data, gives relative coordinates of -.01 ± 0.1, 0.1 ± 0.3, and .1 ± .5 m in the height, East and North directions, respectively. If only a single frequency is determined for the single oscillator used by the two receivers, the results are .01 ± .10, .11 ± .27, and -.06 ± .09 m. These results validate the performance of the receivers and the computational techniques to the 10 cm level achievable with the limited set of test data. Therefore discrepancies above this level discussed in this report seem to be attributable to (1) oscillator, (2) antenna or (3) site-unique conditions.

Statistical analysis was not performed on the absolute station positions which are reported here. The accuracy of absolute positions is limited primarily by the uncertainty in the satellite ephemeris. In the operational GPS system, a different satellite comes into view frequently. If the orbit and satellite clock errors are independent, the effect on absolute position will average out fairly quickly (1 m in 24 hours according to Fell, 1981). In these tests, only four satellites were available, and reference ephemerides were computed for only three independent data spans for each satellite. Day 263 results are based on one ephemeris, days 267-270 are based on a second, and days 275 and 276 are based on a third ephemeris. Therefore the test data would not permit meaningful (1 m or better) tests of the accuracy of absolute station position determinations.

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Table 3. MEAN RELATIVE POSITIONS (m)

Receivers	Case	Frequency Parameters	No. of Solutions	Height	East	North
NSWC/IBM	A	by solution	6	0.4 ± 0.1	0.2 ± 0.3	-0.2 ± 0.1
	B	by pass	6	-1.0 ± 0.6	0.9 ± 0.3	0.2 ± 0.2
	C	60 minute maximum	6	-2.0 ± 0.8	1.4 ± 0.7	-0.2 ± 0.2
Shell/NSWC	A	by solution	5	-1.3 ± 0.6	0.7 ± 0.6	0.3 ± 0.2
	B	by pass	5	-3.1 ± 1.5	-0.1 ± 0.9	-0.7 ± 0.9
	C	60 minute maximum	5	-0.4 ± 0.4	-3.7 ± 1.6	1.3 ± 0.7
IBM/Shell	A	by solution	5	1.5 ± 0.5	-0.7 ± 0.8	0.0 ± 0.2
	B	by pass	5	5.6 ± 1.4	-1.5 ± 1.5	-2.0 ± 0.5
	C	60 minute maximum	5	3.1 ± 0.7	2.5 ± 2.0	-1.2 ± 1.0

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Table 4

CONSISTENCY OF RELATIVE POSITIONS (m)

Receivers	Case	Frequency Parameters	Standard Deviations			Standard Errors			Weighted Residuals
			Height	East	North	Height	East	North	
NSWC/IBM	A	by Solution	0.3	0.7	0.1	0.05	0.03	0.03	2.7
	B	by Pass	1.4	0.7	0.5	0.3	0.2	0.1	2.4
	C	60 Minute Maximum	2.0	1.8	0.4	0.4	0.4	0.2	2.4
Shell/NSWC	A	by Solution	1.4	1.3	0.5	0.07	0.04	0.03	5.9
	B	by Pass	3.4	1.9	2.0	0.3	0.2	0.2	3.8
	C	60 Minute Maximum	2.2	3.6	1.5	0.4	0.4	0.2	5.1
IBM/Shell	A	by Solution	1.1	1.7	0.4	0.08	0.08	0.04	4.9
	B	by Pass	3.2	3.3	1.2	0.3	0.2	0.1	3.7
	C	60 Minute Maximum	1.5	4.5	2.3	0.4	0.4	0.2	3.5
Simulated*		92 Minute Span	0.13	0.22	0.52	0.05	0.12	0.07	

* Simultaneous 4 satellite observations for receivers with an oscillator having characteristics shown in figure 2 for the Efratom Rubidium oscillator (Anderle, 1981)

16

SUMMARY AND PROJECTIONS

For the best set of available oscillators, the relative station position
on a 28 km baseline was computed with a repeatability of 30 cm in height,
70 cm East and 10 cm North based on a 1000 minute Doppler data span, or
a maximum sequential satellite tracking span of 725 minutes. Similar results
can be expected in three hours with a multiplex receiver under development.
A systematic 50 cm bias in the height coordinates is unexplained. The
repeatability was 50 cm to 1.5 m for a receiver with a poorer oscillator.

REFERENCES

Anderle, R. J., "Error Model for Geodetic Positions Derived from Doppler
Satellite Observations", Bulletin Geodesique 50 (1), 43-77, 1976.

Anderle, Richard J., "Application of NAVSTAR GPS Geodetic Receiver to Geodesy
and Geophysics", Annales de Geophysique Tome 37, 37-46, 1981.

Bossler, John D., Clyde C. Good and Peter L. Bender, "Using the Global Positioning
System (GPS) for Geodetic Positioning", Bulletin Geodesique, 54 (4), 553-563,
1980.

Counselman III and I. I. Shapiro, "Miniature Interferometer Terminals for
Earth Surveying: Ambiguity and Multipath with GPS", IEEE Transactions
on Geoscience and Remote Sensing, in press.

Evans, Alan G., Bruce R. Hermann and Patrick J. Fell, "Global Positioning
System Sensitivity Experiment", Naval Surface Weapons Center Technical
Report 81-4, January 1981.

Fell, Patrick J., "Geodetic Positioning Using a Global Positioning System
of Satellites", Department of Geodetic Science Report 299, Ohio State
University, June 1980.

Hermann, Bruce R., "Time Correction of Data from the NAVSTAR Geodetic Receiver
System", Naval Surface Weapons Center Technical Report 81-174, August 1981.

MacDoran, P. F., "Satellite Emission Radio Interferometric Earth Survey
SERIES GPS Geodetic System", Bulletin Geodesique 53 (2), 117-138, 1979.

APPENDIX A

CLOCK CALIBRATIONS

GPS TIME BIAS (MSEC) SHELL
SATELLITE 5

DT = 0.095 + 0.0091x T + 0.00001 XTXT MILLISECONDS
WHERE T = TIME IN DAYS FROM DAY 260

FIGURE 1

A-1

GPS TIME BIAS (MSEC)SHELL
SATELLITE 6

DT= -0.323 + 0.0023X T + 0.00002 XTXT MILLISECONDS
WHERE T= TIME IN DAYS FROM DAY 260
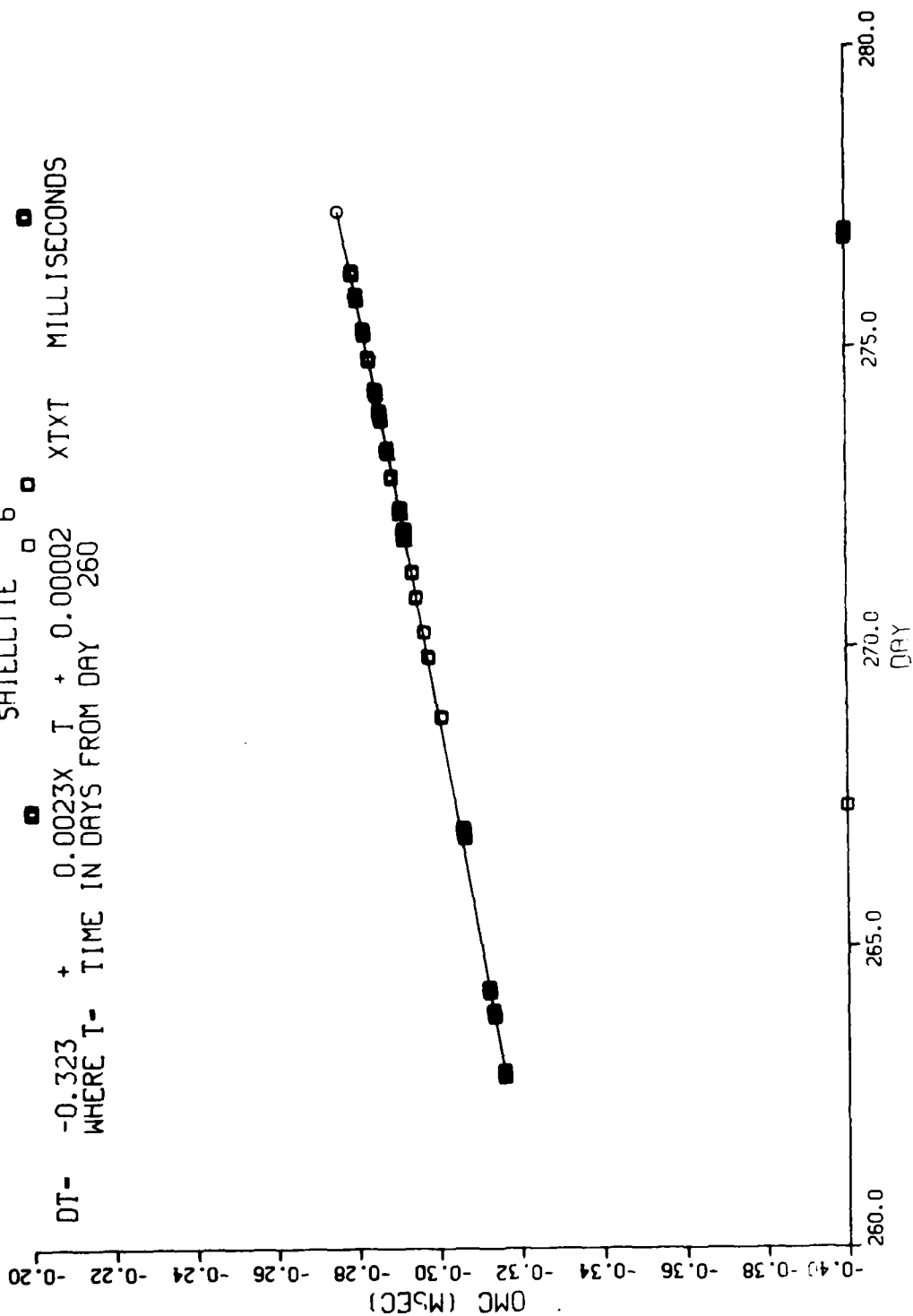
FIGURE 2

GPS TIME BIAS (MSEC) SHELL
SATELLITE 8

DT = 0.397 + 0.0102× T + 0.00003 XTXT MILLISECONDS
WHERE T = TIME IN DAYS FROM DAY 260
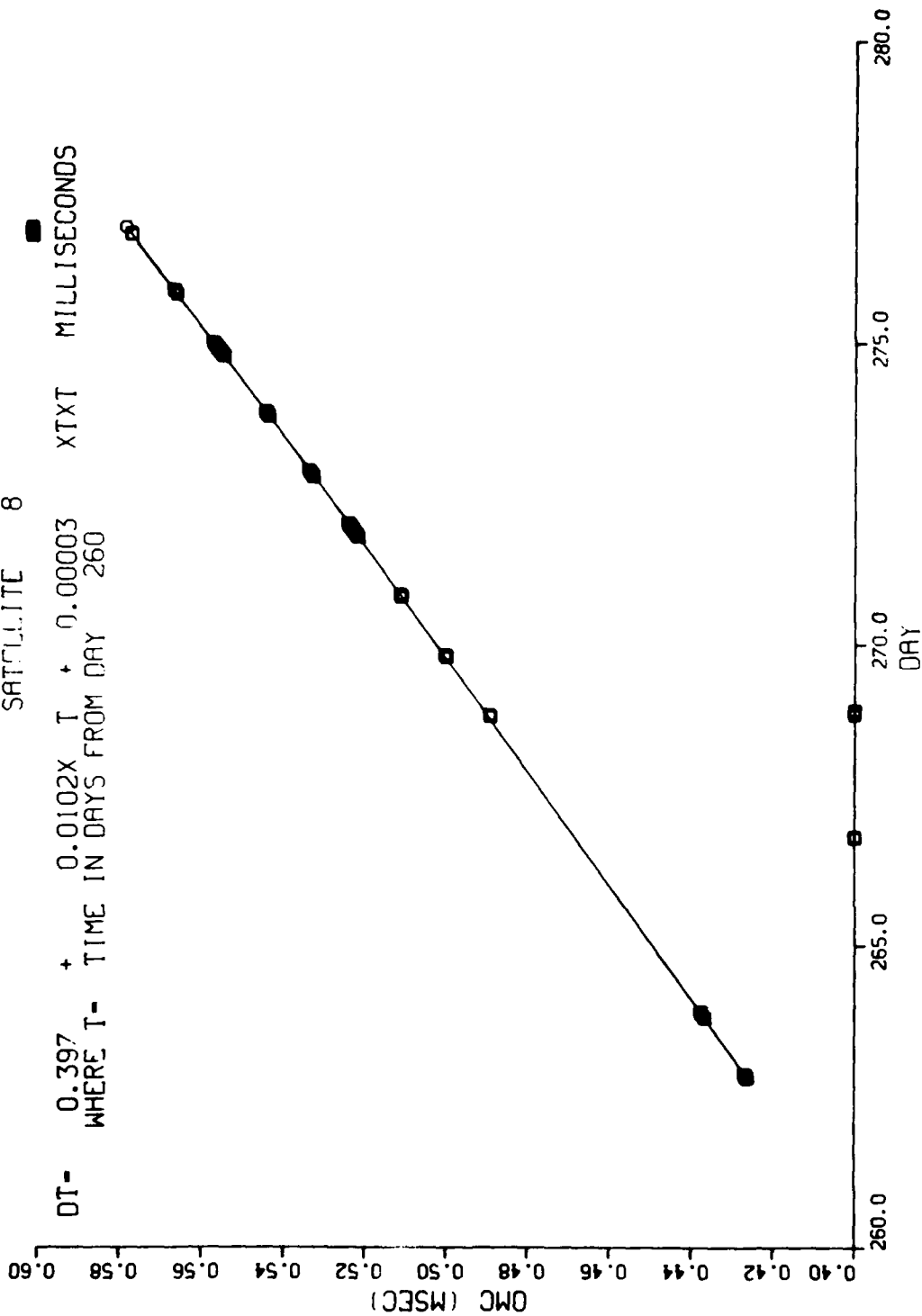
FIGURE 3

A-3

GPS TIME BIAS (MSEC) SHELL

SATELLITE   9

DT = 0.349 + -0.0005x T + 0.00004 XTXT   MILLISECONDS
WHERE T = TIME IN DAYS FROM DAY 260
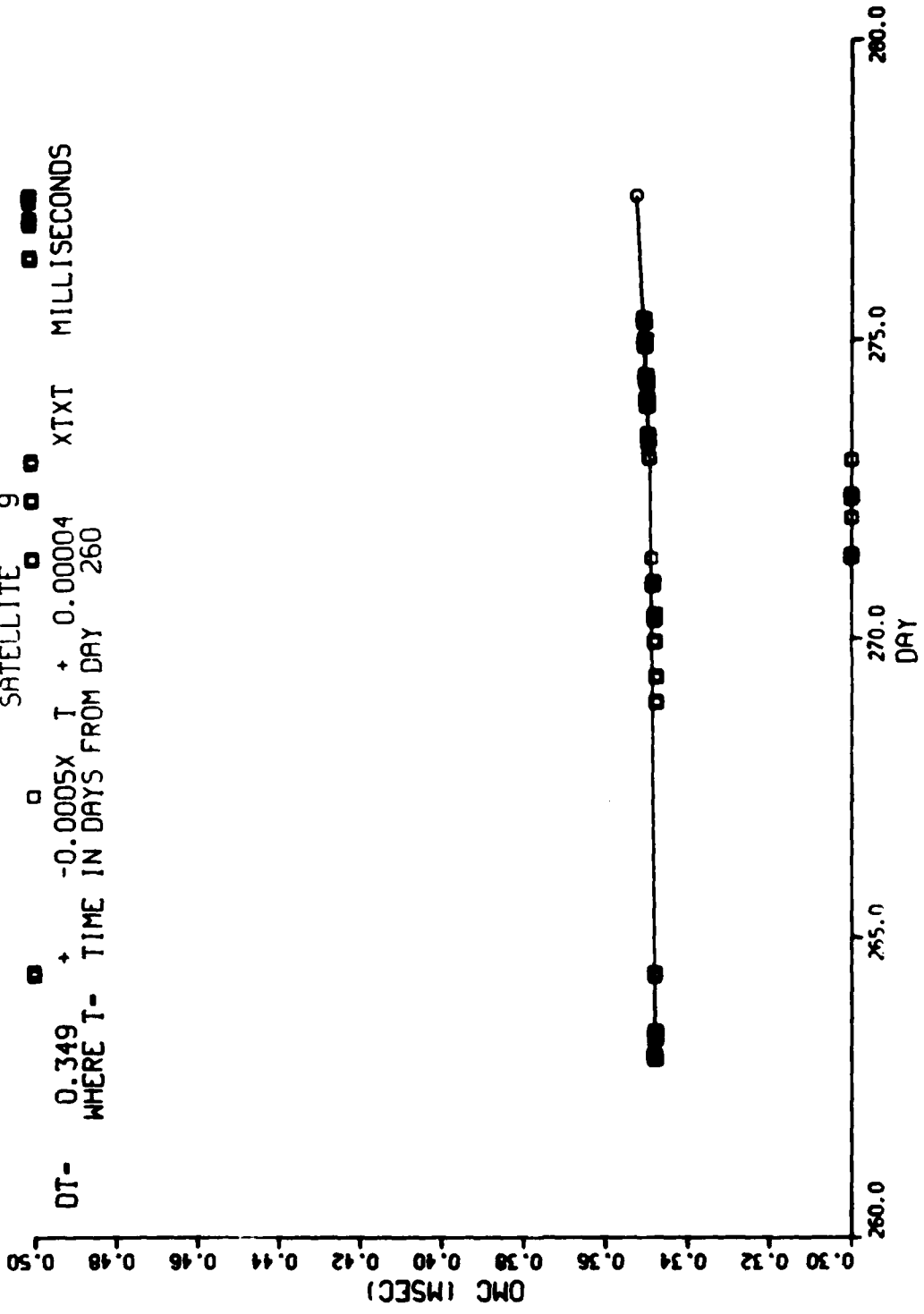
FIGURE 4

A-4
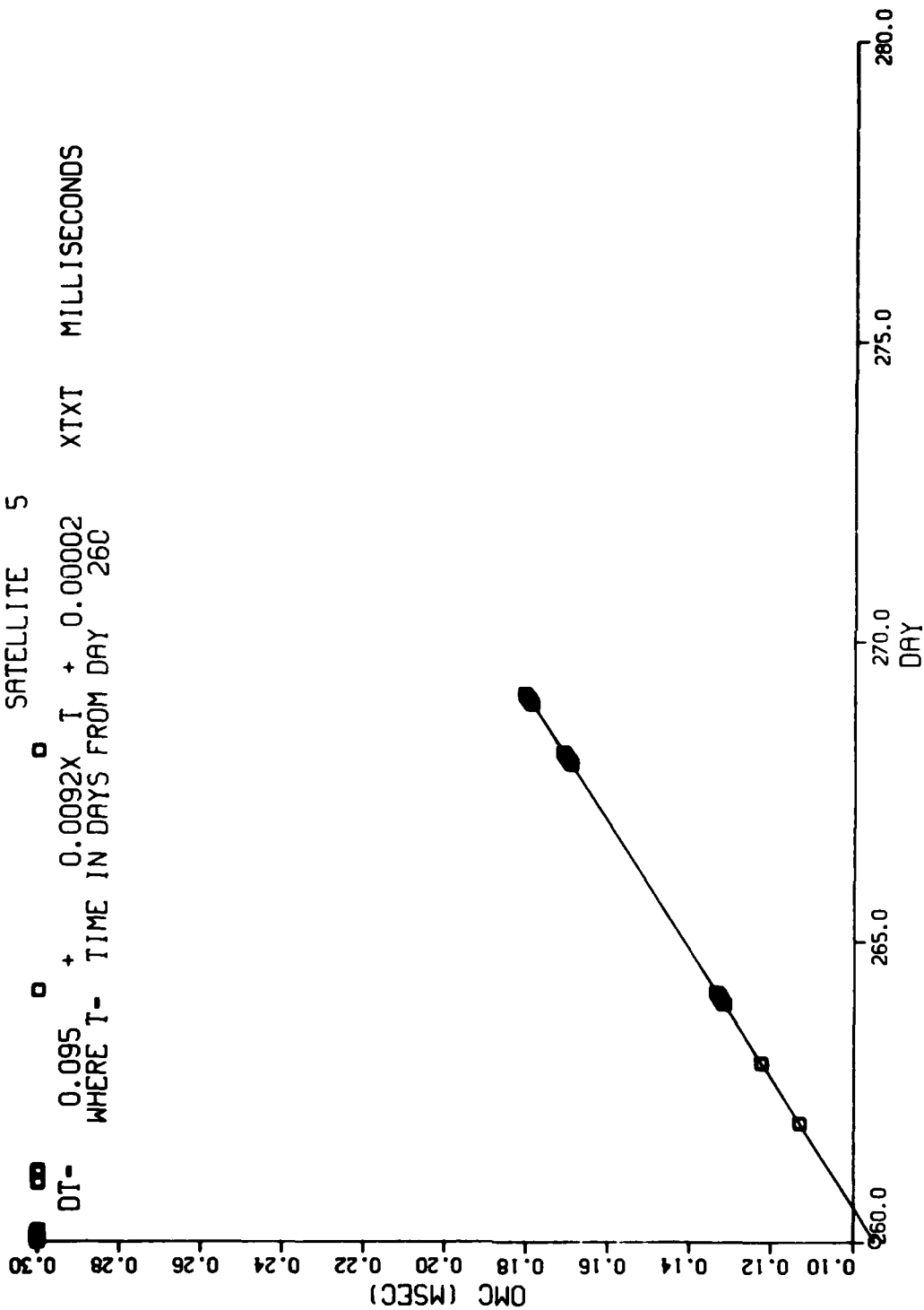
FIGURE 5

GPS TIME BIAS (MSEC) IBM

SATELLITE 6

XTXT   MILLISECONDS

DT= -0.323 + 0.0024x T + 0.00000 260

WHERE T- TIME IN DAYS FROM DAY 260

OMC (MSEC)

DAY

-0.20 -0.22 -0.24 -0.26 -0.28 -0.30 -0.32 -0.34 -0.36 -0.38-0.40

260.0   265.0   270.0   275.0   280.0

FIGURE 6

A-6

GPS TIME BIAS (MSEC) IBM
SATELLITE 8

DT = 0.397 + 0.0103X T + 0.00000 XTXT MILLISECONDS
WHERE T = TIME IN DAYS FROM DAY 260
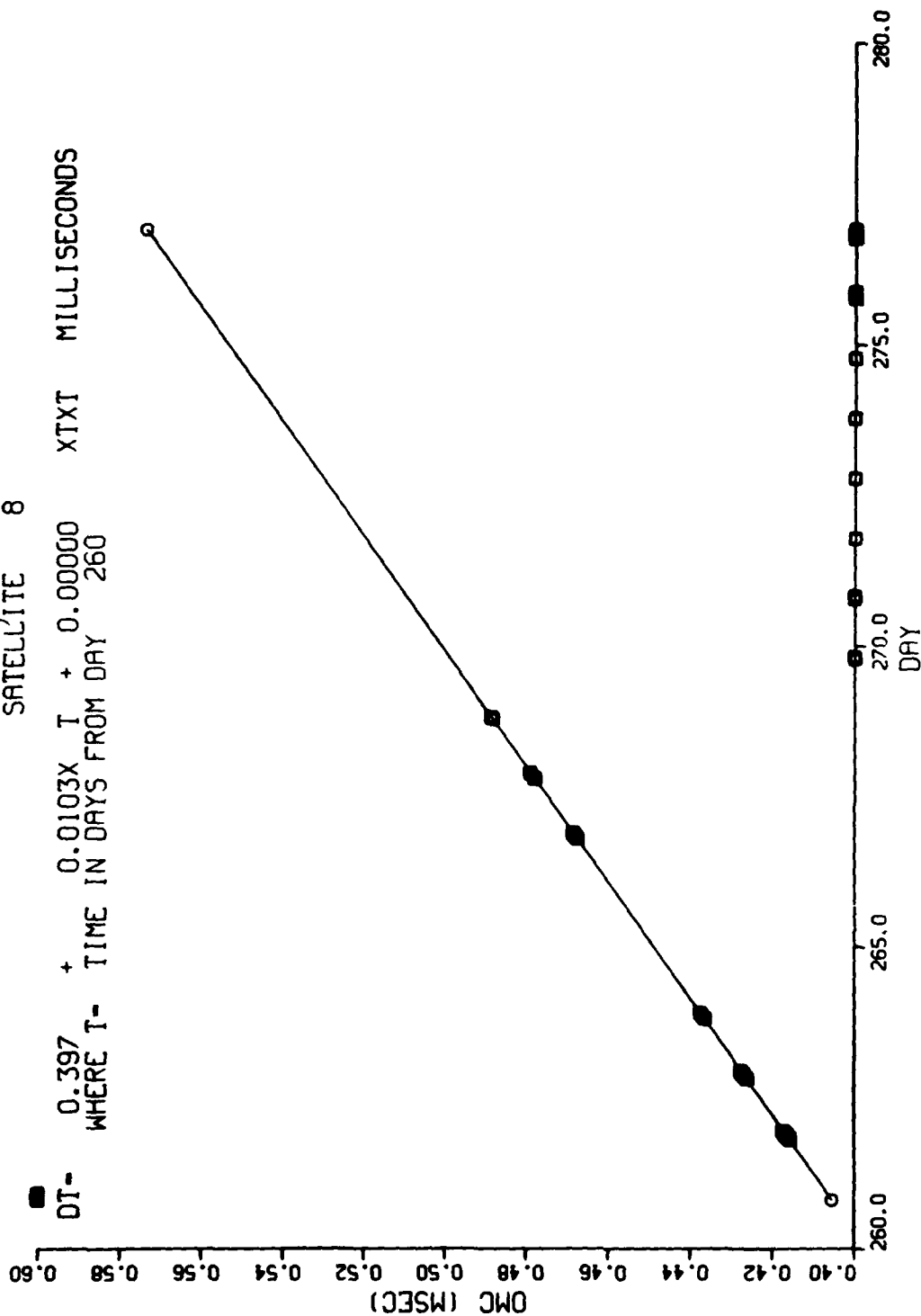
FIGURE 7

A-7

GPS TIME BIAS (MSEC) IBM

SATELLITE 9

DT= 0.349 + -0.0004X T + 0.00002 XTXT MILLISECONDS
WHERE T= TIME IN DAYS FROM DAY 260
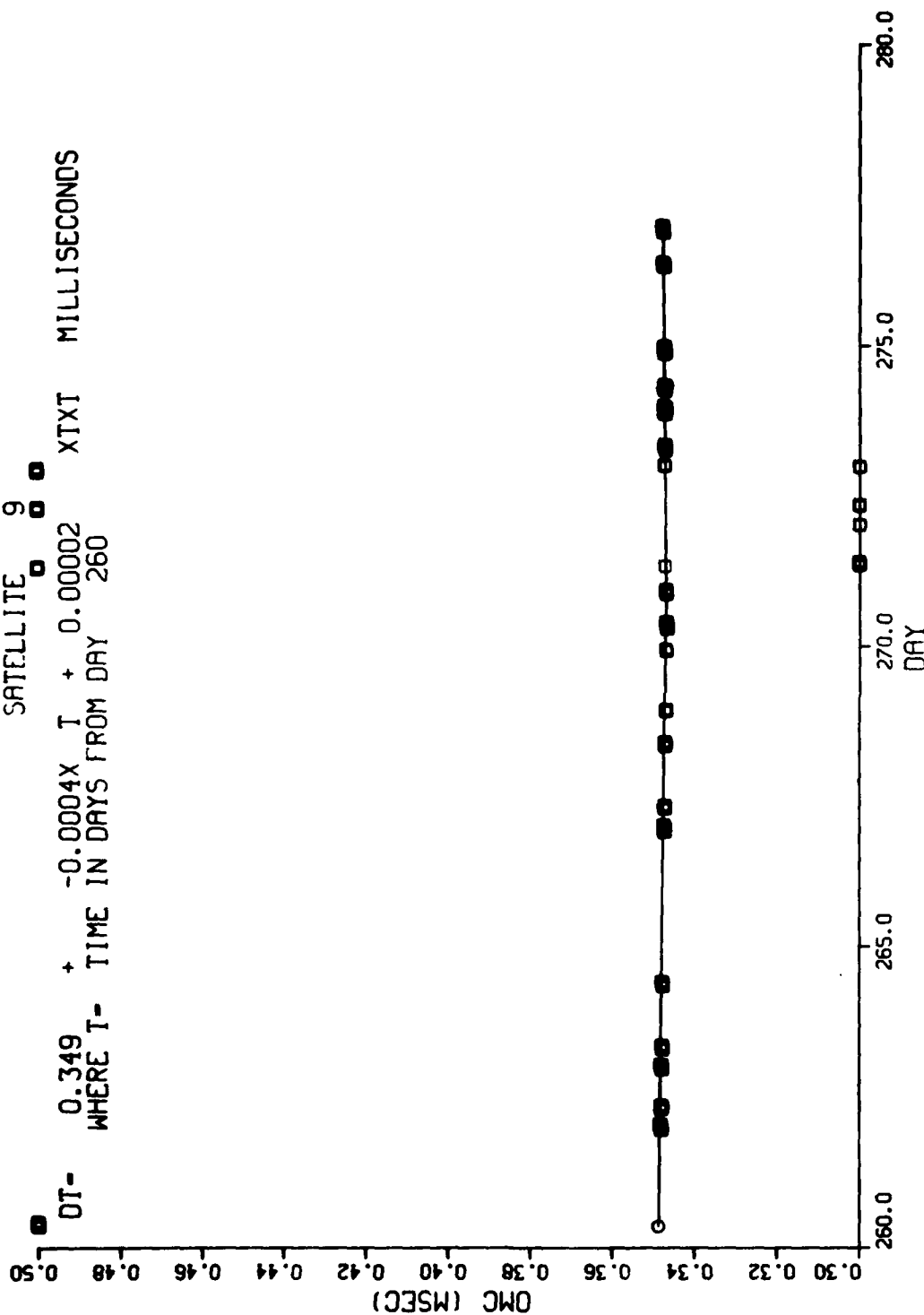
FIGURE 8

A-8

GPS TIME BIAS (MSEC) DV
SATELLITE 9

DT = 0.383 + -0.0001X T + 0.00001 XTXT MILLISECONDS
WHERE T= TIME IN DAYS FROM DAY 260
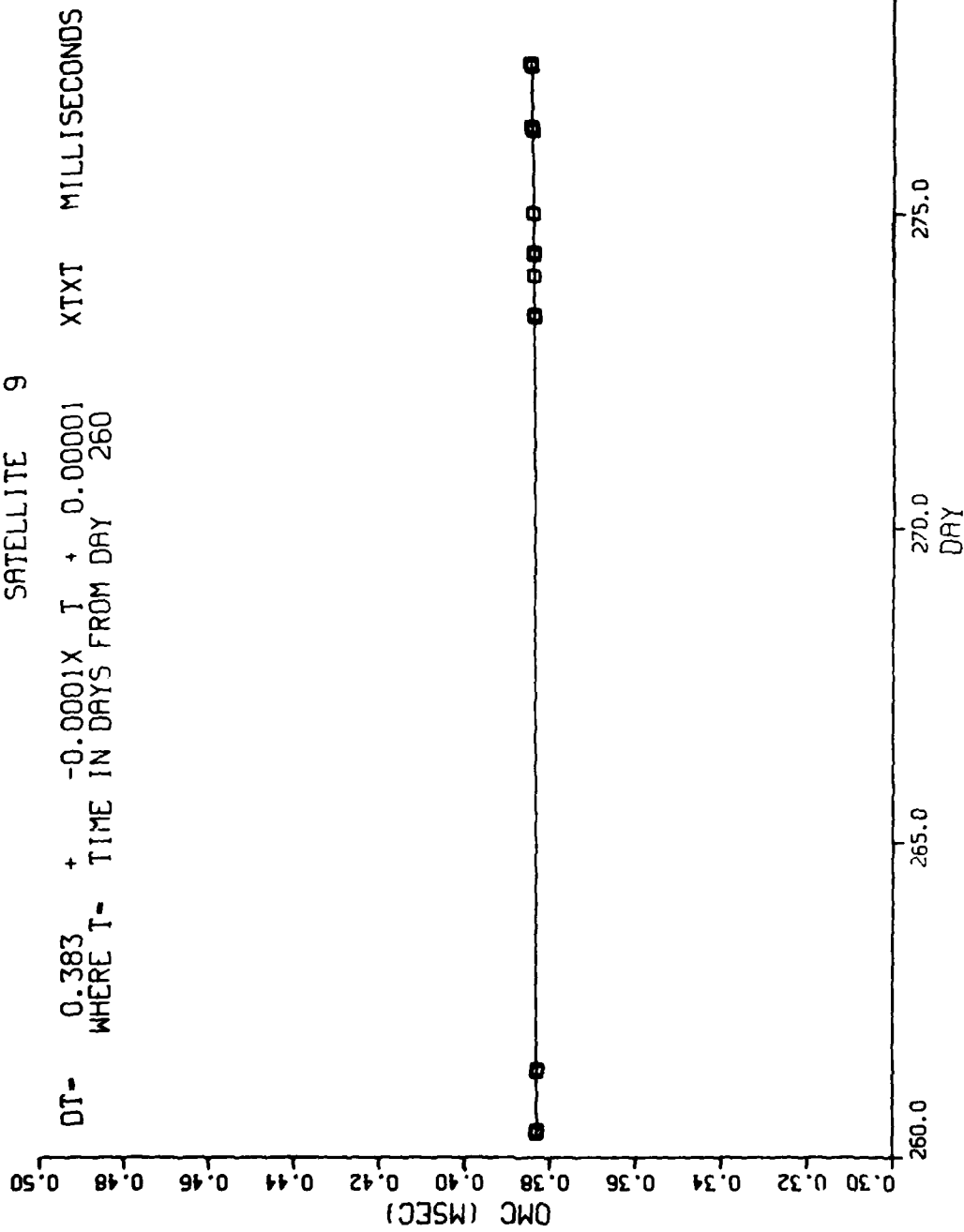
FIGURE 9

A-9

APPENDIX B

OBSERVATIONS AVAILABLE FOR

DOPPLER SOLUTIONS

GPS OBSERVATIONS
IBM/NSWC

B-1

FIGURE 2

B-2
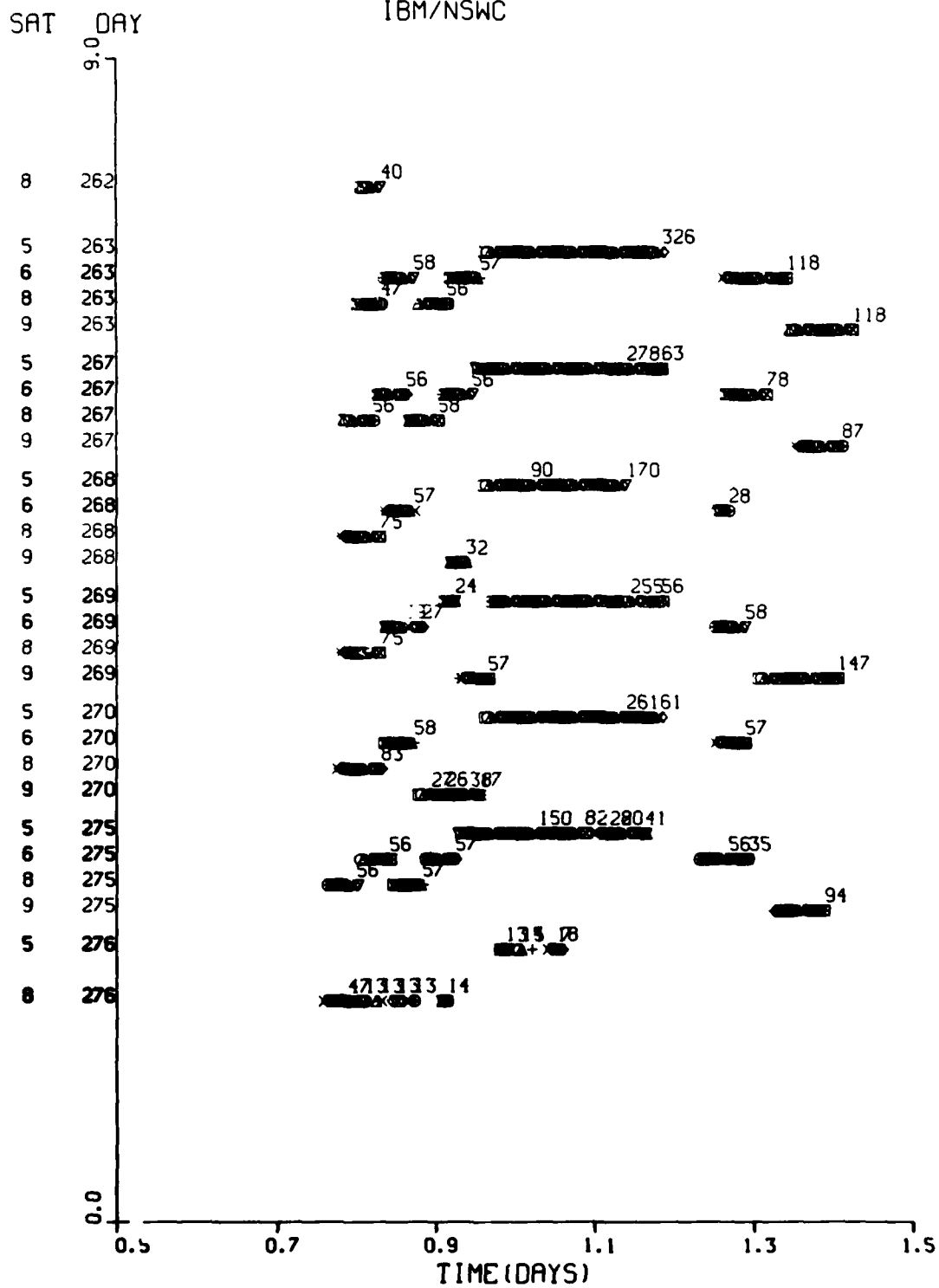
GPS OBSERVATIONS
NSWC/SHELL

FIGURE 3

B-3
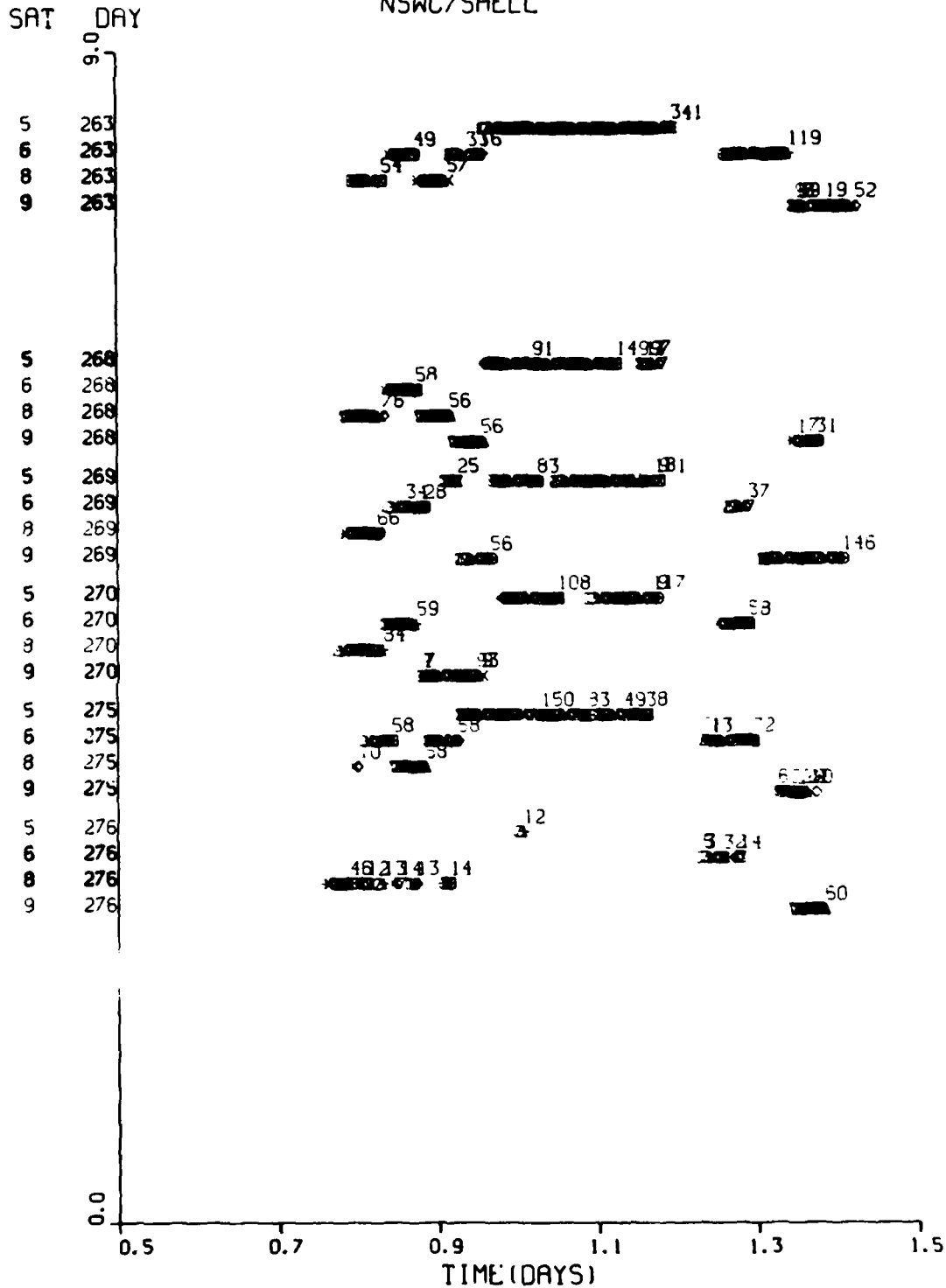
GPS PLOT   NSWC/ IBM

DAY   263.5
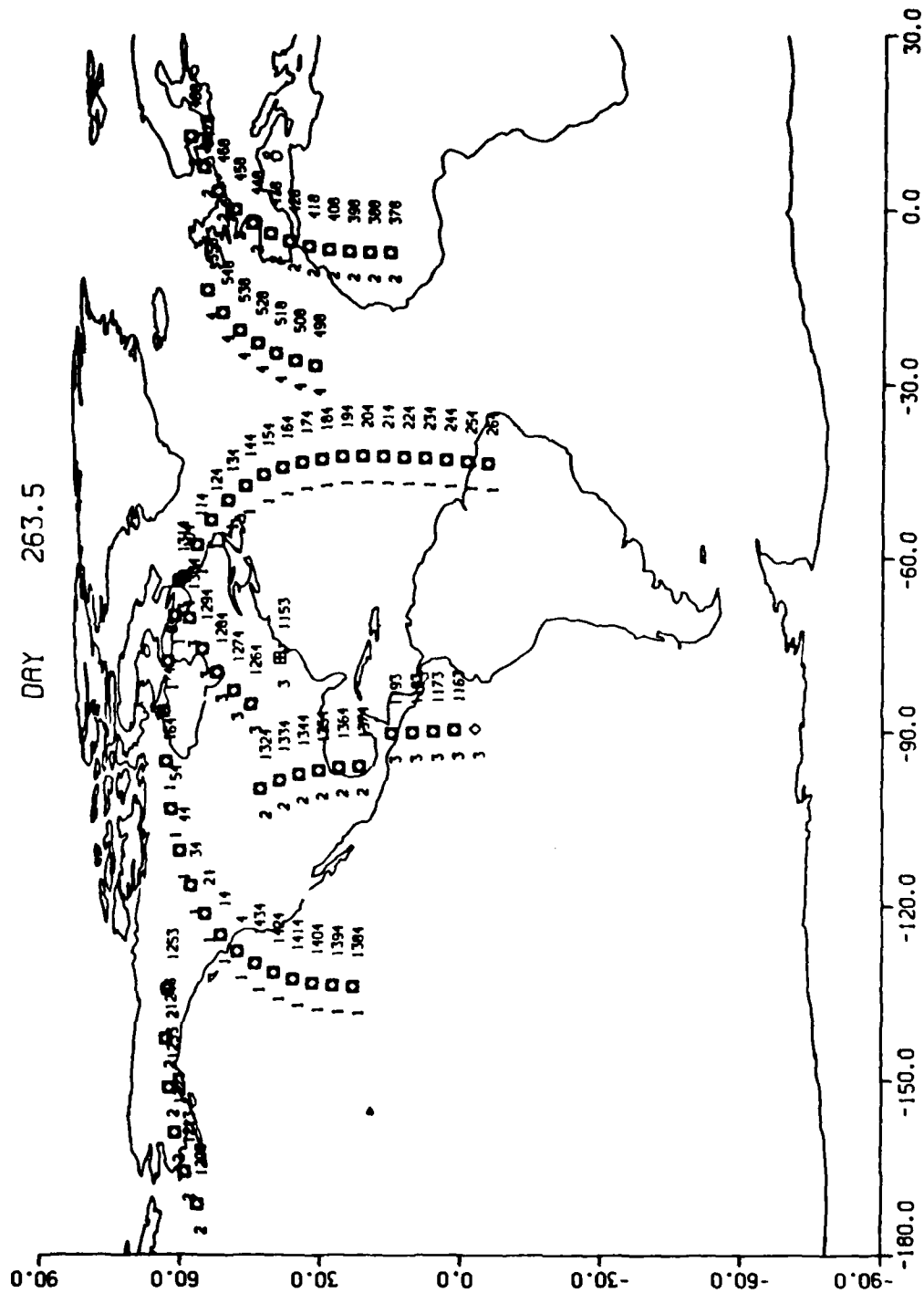
FIGURE 4

B-4

GPS PLOT   NSWC/ IBM

DAY   267.5
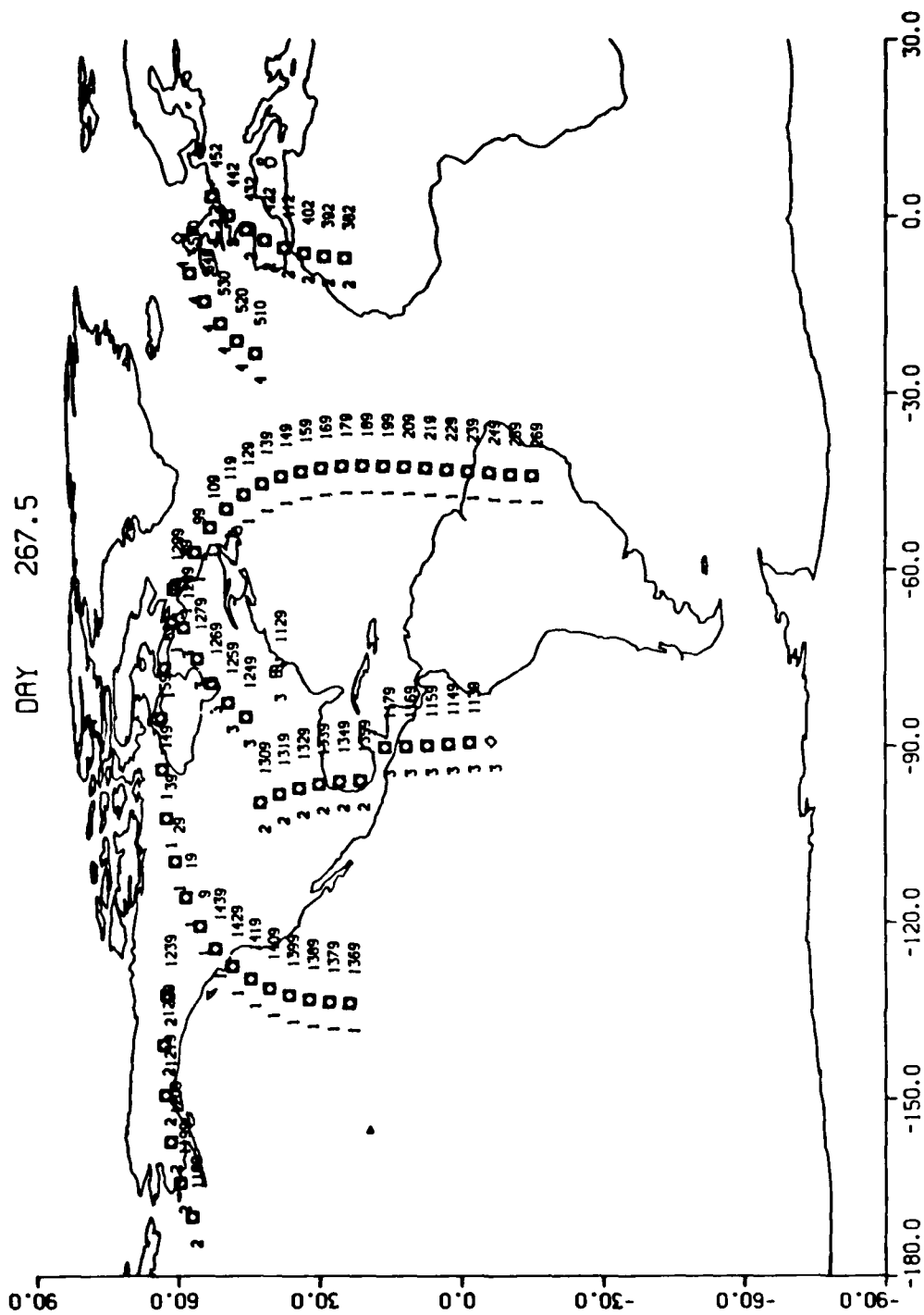
FIGURE 5

B-5

GPS PLOT   NSWC/ IBM
DAY   268.5

FIGURE 6

B-6
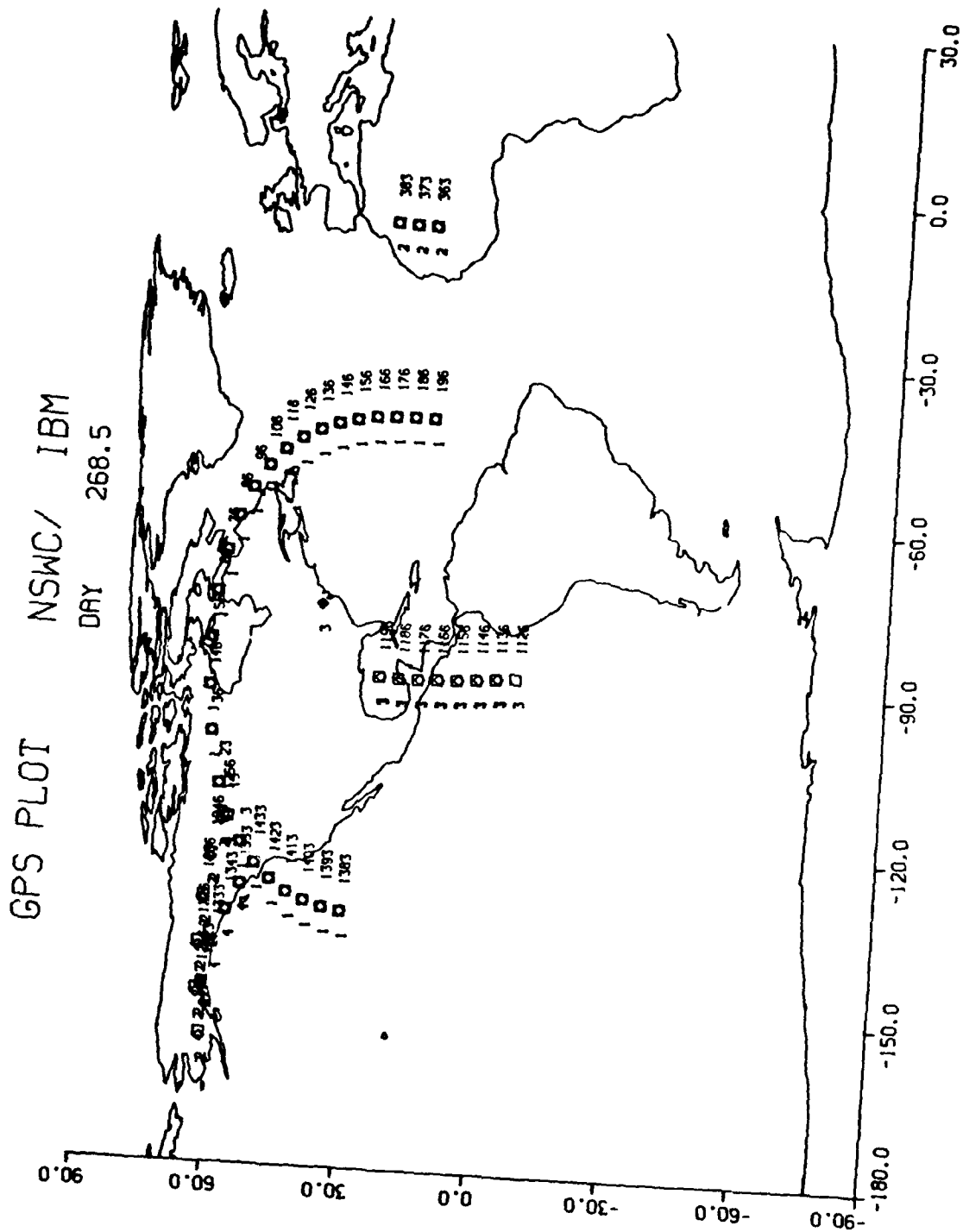
GPS PLOT   NSWC/ IBM
DAY   269.5
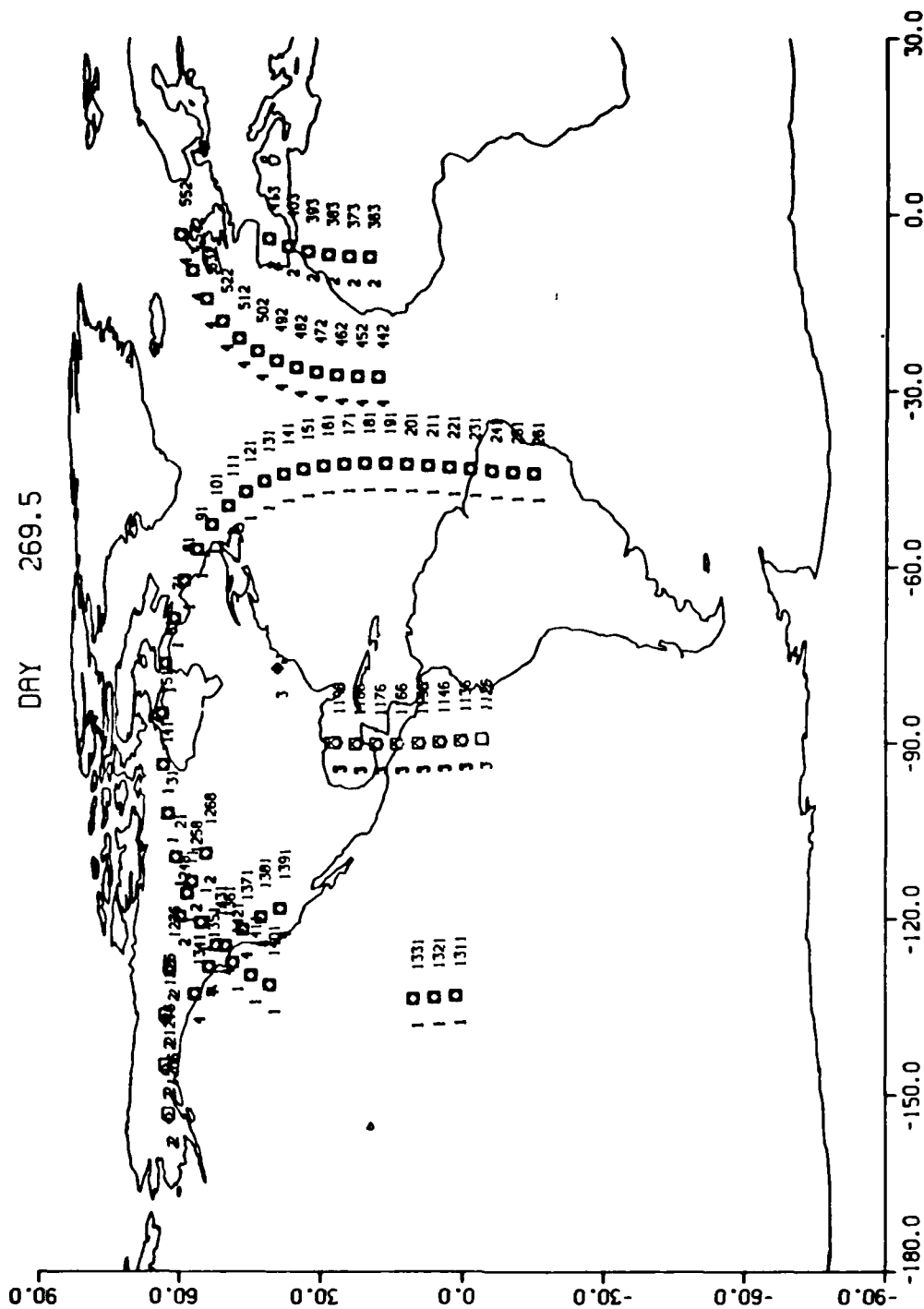
FIGURE 7

B-7

GPS PLOT   NSWC/ IBM
DAY   270.5
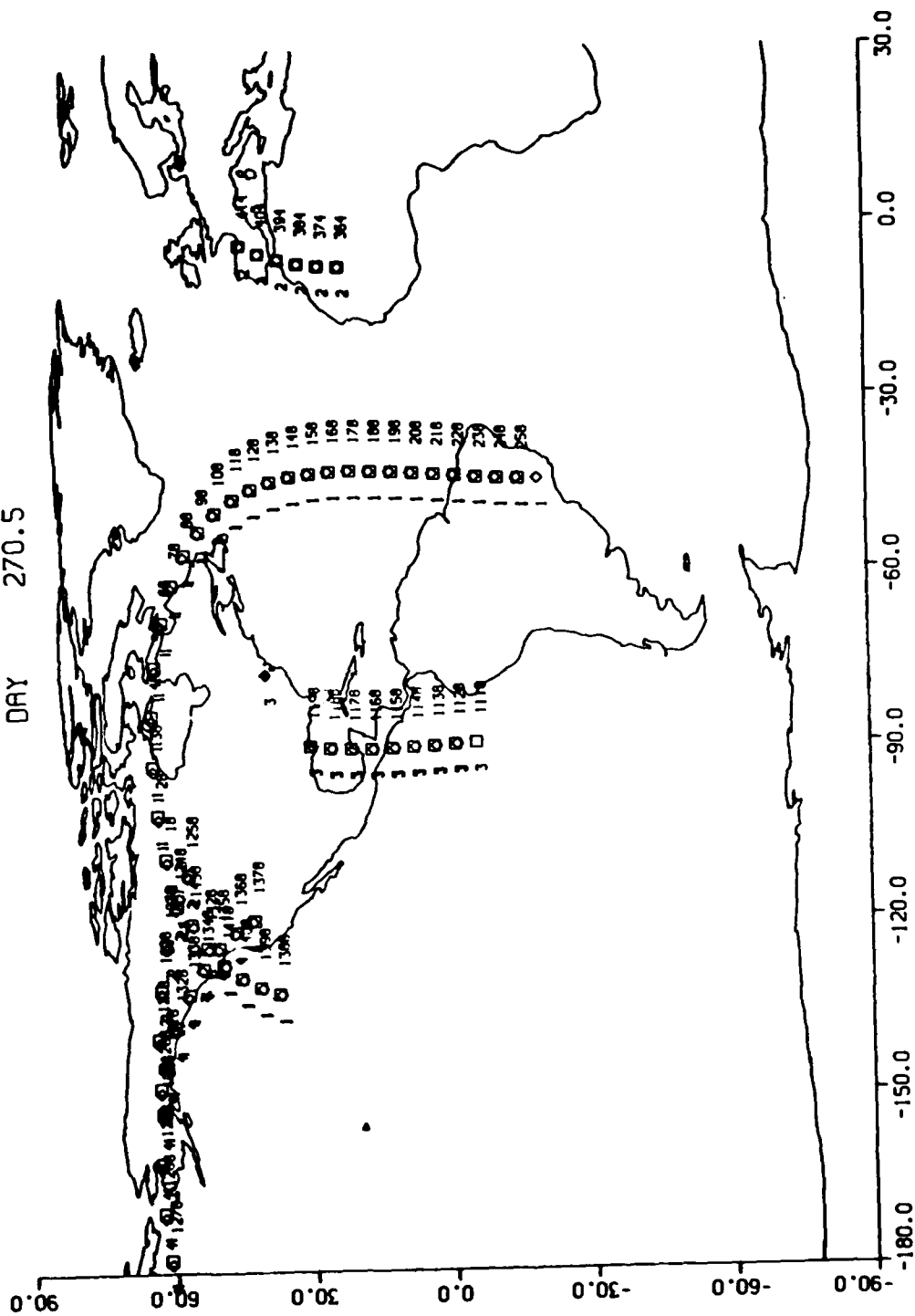
FIGURE 8

B-8

GPS PLOT   NSWC/ IBM
DAY   275.5
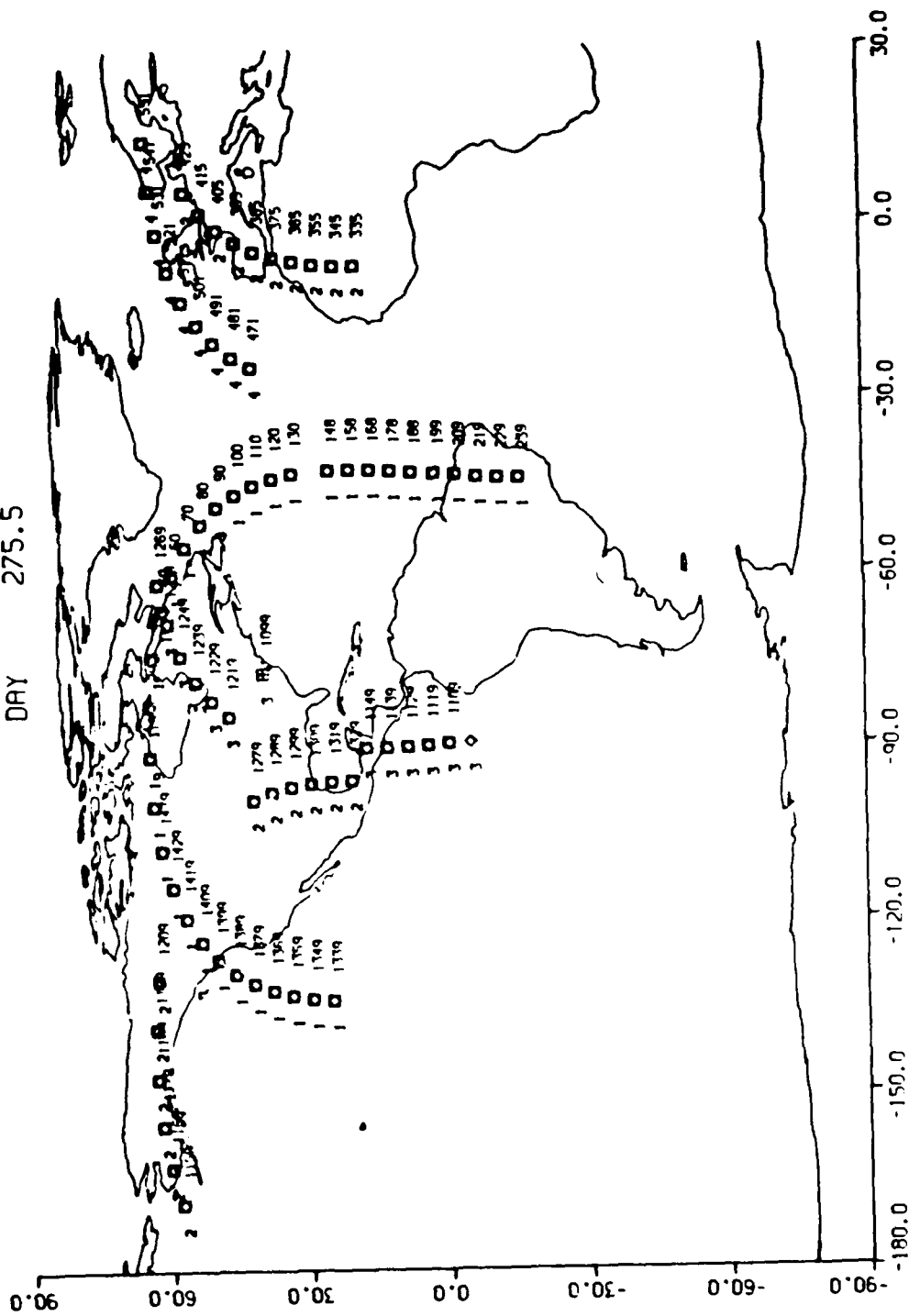
FIGURE 9

GPS PLOT   NSWC/ IBM

DAY   276.5

FIGURE 10

B-10
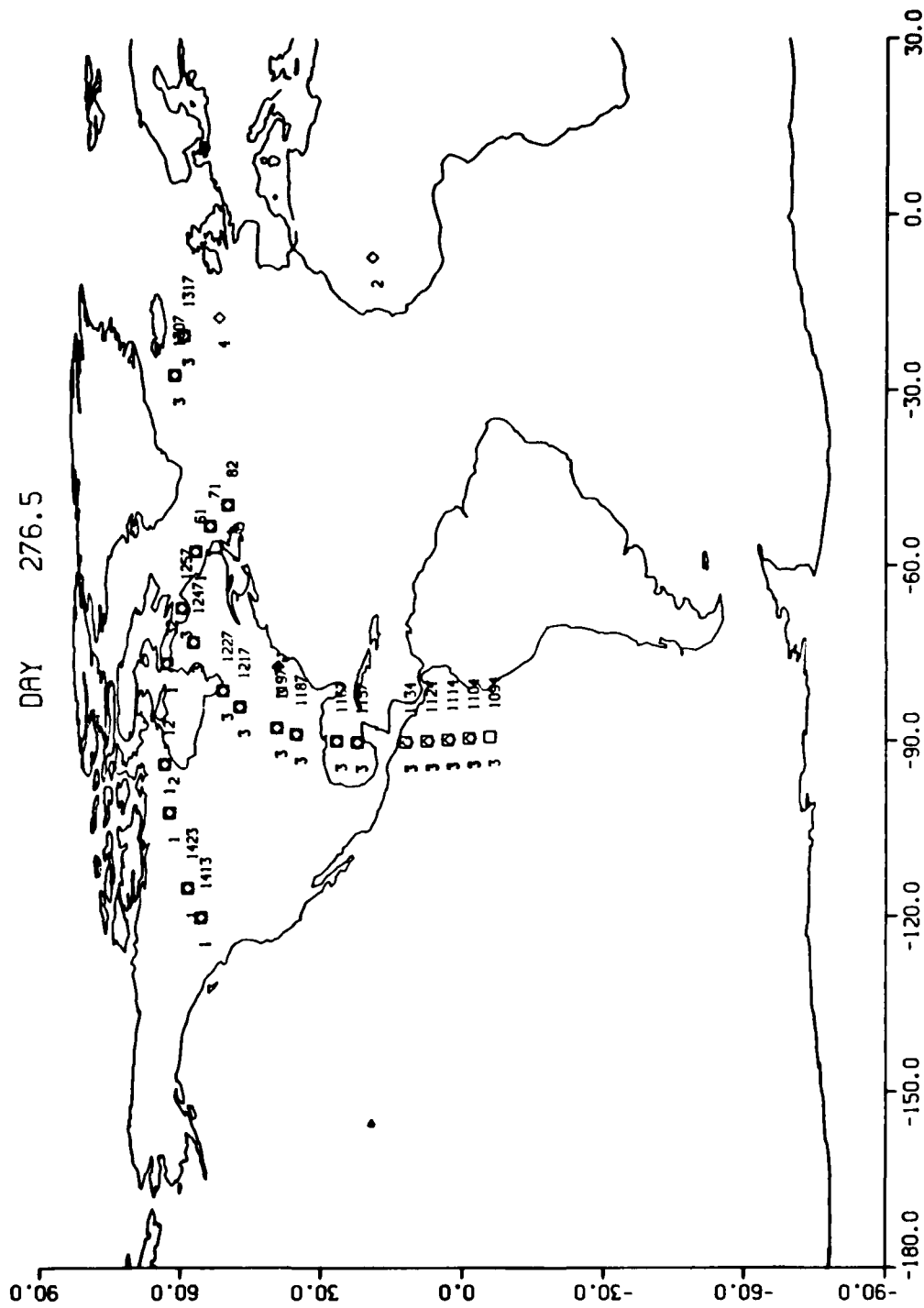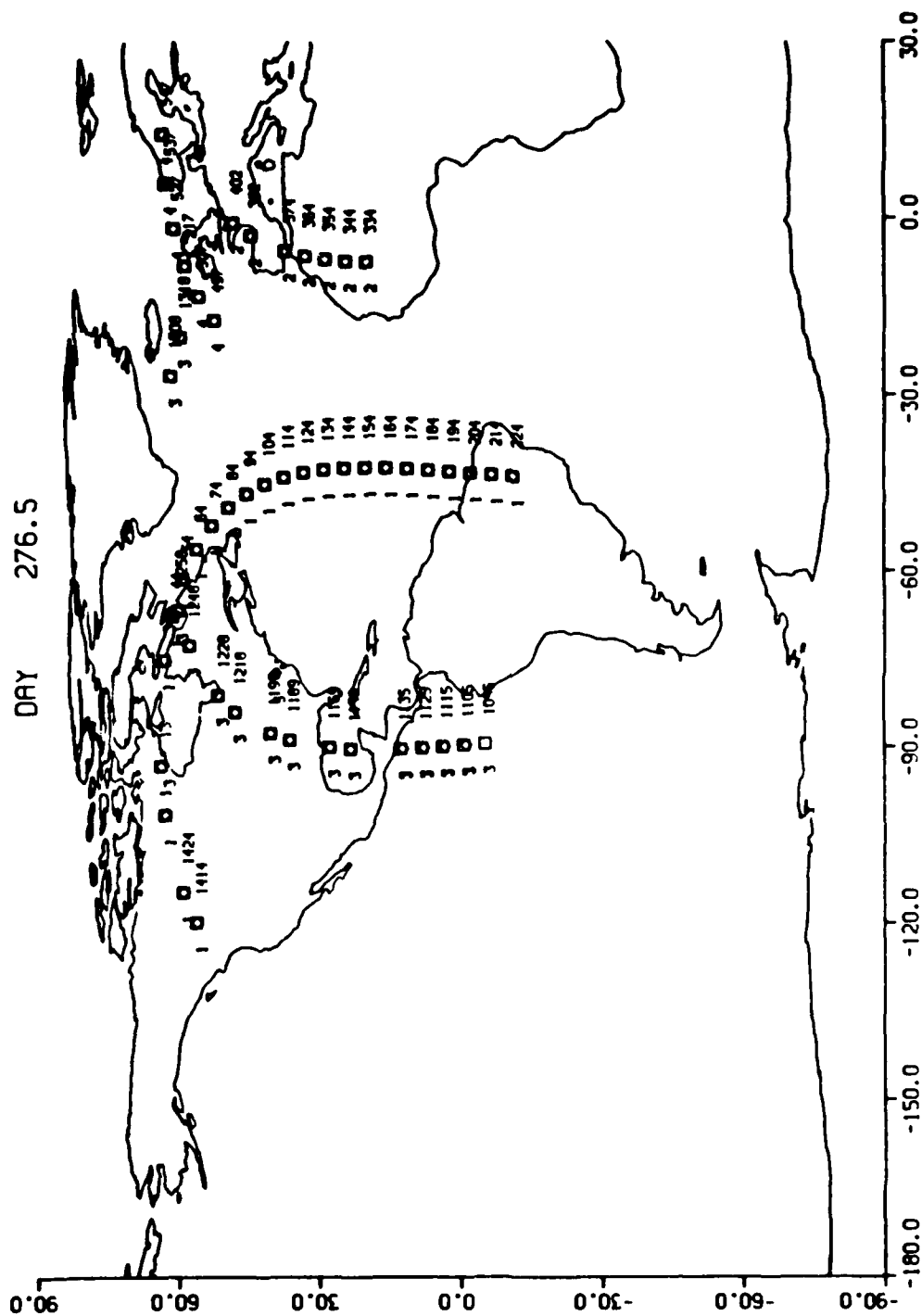
FIGURE 11

B-11

TABLE 1

NUMBER OF POINTS (MINUTES) IN PASS SEGMENTS

DAY	SAT5	SAT6	SAT8	SAT9
NSWC/IBM				
262.5			40	
263.5	326	58,57,118	47,56	118
267.5	278,63	56,56,78	56,58	87
268.5	90,170	57,28	75	32
269.5	24,255,56	39,27,58	75	57,147
270.5	261,61	58,57	83	27,26 38,17
275.5	150,82 28,20,41	56,57 56,35	56,57	94
276.5	13,14,5 18,7		47,13,13, 13,14,14	13
IBM/SHELL				
263.5	328	49,34,16 118	45,56	1,9,17.54
268.5	242	57	74	56
269.5	36,83,142 38,9	67,37	67	54,171
275.5	279,60	57,58,4,13 1,35,58	8,56	11,22,11 12,10,4
276.5	13		44,11,11 11,11,11	
SHELL/NSWC				
263.5	341	49,33 16,119	54,57	9,6,8,9 19,52
268.5	91,149 11,7,7	58	76,56	56,17,31
269.5	25,83 181,9	34,28,37	66	56,146
270.5	108,117,9	59,58	84	2,7,93,9
275.5	150,83 49,38	58,58,2, 13,1,72	10,58	6,22,11, 12,10,4
276.5	12	5,3,32,14	46,12,13, 14,13,14	60

APPENDIX C

DOPPLER SOLUTIONS

TABLE 1

SIX HOUR DOPPLER SOLUTIONS
NSWC RELATIVE TO IBM

CASE A—FREQUENCY PARAMETERS PER SOLUTION

DAY	263	267	268	269	270	275	276
FREQUENCY SOLUTIONS (NS/DAY)							
SAT5	−53±56	74±53	239±57	482±53	129±55	439±54	237±153
SAT6	−147±65	−492±65	−409±129	−1695±81	−896±106	−906±64	−
SAT8	−203±130	−679±124	39±159	−325±153	2115±153	−259±124	205±115
SAT9	928±159	71±174	−551±204	−2031±47	3681±150	−298±150	−
NSWC	−144±1	−157±1	−102±1	−117±1	−148±1	−128±1	−166±21
IBM COORDINATES (M)							
HEIGHT	−5.2±1.9	−0.4±1.9	−9.8±3.2	−19.0±1.9	101.4±2.7	2.3±1.9	2.3±5.1
EAST	8.1±1.6	−5.9±1.8	2.5±2.8	6.6±1.9	−2.6±2.2	−17.5±1.7	−1.5±4.1
NORTH	6.6±1.9	2.1±1.8	11.4±2.2	0.0±1.9	71.7±2.0	3.4±1.9	4.2±3.3
NSWC COORDINATES RELATIVE TO IBM (M)							
HEIGHT	0.6±.05	0.2±.05	0.4±.10	0.6±.05	0.6±.06	0.1±.05	0.0±.5
EAST	0.0 ±03	0.4 ±03	−0.9 ±05	1.2 ±03	−0.2 ±03	0.5 ±03	2.2 ±69
NORTH	−0.1±.02	−0.1±.02	−0.4±.04	−0.2±.02	−0.3±.03	−0.1±.02	−0.1±.32
RMS OF WEIGHTED RESIDUALS							
	1.2	1.6	1.2	1.8	5.8	0.9	0.9

TABLE 2

ORBIT CORRECTIONS FROM CASE A
NSWC/IBM SOLUTIONS

DAY		263	267	268	269	270	275	276
SINE COEFFICIENTS (M)								
RADIAL								
	SAT5	48±3	-9±2	10±4	-19±2	48±3	-8±3	0±5
	SAT6	-45±4	-6±3	-4±4	1±3	-45±4	-8±3	-±
	SAT8	-55±4	-10±3	8±4	11±4	-55±4	-5±3	-2±4
	SAT9	189±4	0±5	-7±5	-1±2	189±4	18±4	-±
TANGENTIAL								
	SAT5	-53±7	19±7	31±8	-8±6	-53±7	3±8	4±10
	SAT6	120±8	23±5	28±8	41±8	120±8	23±7	-±
	SAT8	17±8	-5±6	-2±8	-26±7	17±8	11±6	-5±8
	SAT9	272±7	26±8	16±9	-43±6	272±7	-4±7	-±
NORMAL								
	SAT5	0±5	-9±4	-65±6	28±3	0±5	-4±7	5±14
	SAT6	49±10	-13±7	-32±11	-20±9	49±10	-27±8	-±
	SAT8	0±14	-11±12	32±14	-22±14	0±13	32±12	40±8
	SAT9	540±16	-3±11	15±12	-14±9	540±10	23±11	-±
COSINE COEFFICIENTS (M)								
RADIAL								
	SAT5	98±3	5±3	11±3	-9±3	98±3	-2±3	-1±4
	SAT6	-3±3	7±2	-5±3	16±3	-3±2	-8±3	-±
	SAT8	0±4	6±4	8±4	1±4	0±4	-8±3	-4±4
	SAT9	-183±4	-3±4	-4±5	31±2	-180±4	0±4	-±
TANGENTIAL								
	SAT5	43±7	20±7	-25±8	53±7	43±7	-7±7	-2±8
	SAT6	-28±8	4±7	10±8	3±7	-28±8	-3±7	-±
	SAT8	-103±8	3±7	3±8	17±8	-103±8	-17±8	4±8
	SAT9	-184±8	-1±8	-13±8	11±8	-184±8	-2±8	-±
NORMAL								
	SAT5	-11±5	-7±5	-1±7	-40±5	-11±5	15±7	4±14
	SAT6	183±11	-2±8	33±11	47±10	183±11	-4±10	-±
	SAT8	57±12	20±8	-3±12	-6±12	57±12	11±11	-16±9
	SAT9	91±3	40±12	23±14	142±9	91±10	3±11	-±

TABLE 3

SIX HOUR DOPPLER SOLUTIONS
NSWC RELATIVE TO IBM

CASE B-FREQUENCY PARAMETERS EACH PASS

DAY	263	267	268	269	270	275	276
FREQUENCY SOLUTIONS-LAST PASS (NS/DAY)							
SAT 5	-55±57	-140±56	256±58	315±57	-75±57	380±58	58±149
SAT 6	-197±83	-147±96	-445±147	-1917±125	-730±124	-657±95	-±
SAT 8	-192±170	-553±117	69±160	-243±155	2155±153	69±118	18±163
SAT 9	867±160	151±176	-686±206	-1386±107	6464±129	-302±151	-±
NSWC	-155±3	-209±8	-42±17	-124±3	-225±5	-97±9	-±
IBM COORDINATES (M)							
HEIGHT	-4.5±1.9	1.7±2.0	-14.5±3.3	-20.8±2.1	124.1±2.8	2.1±2.0	-14.9±4.7
EAST	8.1±2.0	-7.4±2.2	8.5±3.2	4.1±2.2	-11.0±2.5	-12.1±2.4	-12.6±4.4
NORTH	6.0±1.9	6.4±1.9	13.3±2.4	6.3±2.2	67.0±2.2	4.1±2.0	8.1±3.9
NSWC COORDINATES RELATIVE TO IBM (M)							
HEIGHT	-0.0±0.2	-3.0±0.3	-1.8±0.3	0.6±0.1	-1.5±0.3	0.2±0.3	-1.0±1.7
EAST	0.3±0.1	2.0±0.1	0.5±0.2	1.3±0.1	-0.1±0.1	1.2±0.2	-3.4±1.1
NORTH	0.2±0.1	1.0±0.1	-0.2±0.2	0.1±0.1	0.9±0.1	-0.3±0.2	-1.0±0.9
RMS OF WEIGHTED RESIDUALS							
	1.15	1.50	1.10	1.60	8.38	1.11	0.76

TABLE 4

SIX HOUR DOPPLER SOLUTIONS
NSWC RELATIVE TO IBM

CASE C-FREQUENCY PARAMETER MAX. SPAN=60 MIN.

DAY	263	267	268	269	270	275	276
FREQUENCY SOLUTIONS (NS/DAY)							
SAT5	−69±56	−166±56	155±57	79±61	−550±60	131±58	163±139
SAT6	−133±90	−327±98	−222±151	−1553±126	−298±128	−554±95	−
SAT8	114±120	−490±113	−57±146	−504±143	1750±141	40±113	69±103
SAT9	−±	27±176	−286±209	−1779±105	3364±136	−278±135	−
NSWC	−153±9	−144±13	−32±22	−155±10	−103±13	−158±19	−±
IBM COORDINATES (M)							
HEIGHT	−5.6±2.1	0.5±2.1	0.5±3.6	−13.7±2.2	127.6±2.9	2.9±2.0	2.7±5.1
EAST	9.1±2.5	−10.0±2.7	−0.3±3.5	−17.9±2.6	−24.7±2.8	−15.5±2.6	−3.1±4.2
NORTH	5.1±2.0	−1.0±2.0	2.8±2.6	−0.8±2.5	53.1±2.3	2.4±2.0	3.9±3.5
NSWC COORDINATES RELATIVE TO IBM (M)							
HEIGHT	0.3±0.3	−0.6±0.4	−3.9±0.6	−1.9±0.4	−4.9±0.5	−1.1±0.4	−1.5±1.5
EAST	−0.3±0.3	1.2±0.4	−0.8±0.5	1.7±0.4	4.0±0.4	2.8±0.5	−1.8±1=5
NORTH	0.1±0.1	−0.2±0.3	0.2±0.2	−0.7±0.2	0.4±0.1	−0.7±0.3	−3.1±0.9
RMS OF WEIGHTED RESIDUALS							
	1.0	1.2	0.9	1.3	5.6	1.0	0.8

TABLE 5

SIX HOUR DOPPLER SOLUTIONS
IBM RELATIVE TO SHELL

CASE A—FREQUENCY PARAMETERS PER SOLUTION

DAY	263*	268	269	270	275
FREQUENCY SOLUTIONS (NS/DAY)					
SAT5	718±56	872±54	1580±49	238±61	1422±49
SAT6	−542±66	460±175	−2026±91	461±112	−499±64
SAT8	534±131	301±160	−680±158	1929±154	−1688±150
SAT9	−199±203	−213±169	−1854±48	4187±152	−273±156
IBM	153±1	350±1	405±1	363±1	402±1
SHELL COORDINATES (M)					
HEIGHT	−13.0±1.9	5.0±3.5	−45.2±1.9	137.6±2.8	0.1±1.8
EAST	15.3±1.6	4.3±3.5	20.5±2.0	−50.0±2.6	−30.2±1.7
NORTH	3.1±1.9	−9.0±2.5	−11.3±1.9	62.6±2.1	−18.5±1.8
IBM COORDINATES RELATIVE TO SHELL (M)					
HEIGHT	1.7±.06	3.0±.09	1.6±.04	1.4±.06	−0.1±.06
EAST	−2.0±.03	−0.3±.06	−0.7±.04	1.7±.05	−2.5±.04
NORTH	−0.7±.02	−0.3±.04	0.2±.02	0.1±.03	0.4±.03
RMS OF WEIGHTED RESIDUALS					
	5.1	2.5	2.9	6.7	2.5

TABLE 6

ORBIT CORRECTIONS FROM CASE A
IBM/SHELL SOLUTIONS

DAY		263	268	269	270	275
SINE COEFFICIENTS (M)						
RADIAL						
	SAT5	6 ±2	−4 ±4	−47 ±2	25 ±3	−42 2
	SAT6	3 ±3	2 ±6	20 ±3	−17 ±4	0 ±3
	SAT8	19 ±3	−4 ±4	19 ±4	−85 ±4	−7 ±4
	SAT9	4 ±5	−6 ±4	−13 ±2	223 ±4	7 ±4
TANGENTIAL						
	SAT5	68 ±7	44 ±8	−8 ±6	−14 ±8	145 ±7
	SAT6	75 ±5	41 ±8	27 ±8	142 ±8	10 ±4
	SAT8	5 6	−5 8	−31 8	67 8	31 6
	SAT9	−1 ±9	−36 ±8	−36 ±6	218 ±7	7 ±7
NORMAL						
	SAT5	−115 ±5	−56 ±7	30 ±3	61 ±7	−74 ±5
	SAT6	29 ±8	38 ±11	9 ±9	170 ±10	19 ±7
	SAT8	59 ±12	−64 ±14	44 ±13	−30 ±13	130 ±13
	SAT9	−18 ±11	43 ±11	−7 ±9	639 ±10	−14 ±11
COSINE COEFFICIENTS						
RADIAL						
	SAT5	15 ±3	1 ±4	−16 ±3	103 ±3	18 ±3
	SAT6	19 ±2	−5 ±4	19 ±3	−18 ±2	19 ±2
	SAT8	−4 ±4	12 ±4	5 ±4	−20 ±4	17 ±4
	SAT9	−2 ±4	11 ±5	26 ±2	−205 ±4	−1 ±4
TANGENTIAL						
	SAT5	39 ±8	51 ±8	148 ±7	17 ±8	62 ±6
	SAT6	22 ±7	4 ±9	−18 ±8	−29 ±8	26 ±7
	SAT8	15 ±7	27 ±8	18 ±8	−176 ±8	26 ±8
	SAT9	11 ±9	23 ±8	93 ±7	−192 ±8	11 ±8
NORMAL						
	SAT5	−7 ±6	−21 ±7	−117 ±5	119 ±6	−37 ±5
	SAT6	−83 ±6	−27 ±12	25 ±9	148 ±11	4 ±6
	SAT8	−15 ±9	−8 ±13	2 ±12	59 ±12	265 ±12
	SAT9	1 ±14	64 ±12	126 ±8	33 ±10	6 ±12

TABLE 7

SIX HOUR DOPPLER SOLUTIONS
IBM RELATIVE TO SHELL

CASE B-FREQUENCY PARAMETERS EACH PASS

DAY	263*	268	269	270	275
FREQUENCY SOLUTIONS-LAST PASS (NS/DAY)					
SAT5	611±57	418±58	625±75	382±82	552±56
SAT6	-153±86	-35±176	-1944±121	-1516±130	-215±97
SAT8	803±121	262±160	-391±160	641±175	840±161
SAT9	-60±174	-363±170	-562±110	2491±122	-324±145
IBM	264±18	348±4	495±9	403±8	180±89
SHELL COORDINATES (M)					
HEIGHT	-26.4±2.0	-4.5±3.5	-40.4±2.1	46.1±3.0	-5.3±2.1
EAST	40.3±2.1	-9.6±3.6	8.4±2.5	-28.7±3.1	-8.6±2.2
NORTH	0.6±1.9	2.1±2.5	9.2±2.3	17.5±2.3	-3.5±1.9
IBM COORDINATES RELATIVE TO SHELL (M)					
HEIGHT	8.7±0.2	2.7±0.3	2.2±0.1	9.0±0.3	5.6±0.3
EAST	-1.2±0.1	-0.4±0.2	1.6±0.2	1.3±0.3	-5.6±0.1
NORTH	-3.7±0.1	-0.7±0.1	-1.1±0.2	-2.7±0.1	-2.0±0.1
RMS OF WEIGHTED RESIDUALS					
	4.7	2.1	2.6	5.8	1.9

TABLE 8

SIX HOUR DOPPLER SOLUTIONS
IBM RELATIVE TO SHELL

CASE C-FREQUENCY PARAMETER MAX. SPAN=60 MIN.

DAY	263	268	269	270	275

FREQUENCY SOLUTIONS–LAST PASS (NS/DAY)

	263	268	269	270	275
SAT5	465±56	449±58	460±75	-143±121	675±56
SAT6	212±92	-380±181	-2102±128	-141±132	-131±97
SAT8	-122±121	426±146	-415±145	1452±142	446±145
SAT9	-239±204	-348±172	-800±100	3338±138	-52±141
IBM	63±18	54±15	537±10	531±13	467±35

SHELL COORDINATES (M)

	263	268	269	270	275
HEIGHT	-3.3±2.1	-2.2±3.8	-45.1±2.3	113.4±3.0	-5.0±2.
EAST	-9.5±2.8	-16.1±3.7	3.6±2.6	-52.1±3.2	-5.5±2.5
NORTH	-5.3±2.0	5.4±2.7	1.4±2.3	44.1±2.3	-0.1±2.0

IBM COORDINATES RELATIVE TO SHELL (M)

	263	268	269	270	275
HEIGHT	4.3±0.3	1.4±0.5	4.7±0.4	3.3±0.5	1.7±0.4
EAST	0.6±0.3	6.7±0.5	0.9±0.4	7.5±0.4	-3.2±0.4
NORTH	1.8±0.1	-4.6±0.2	-1.2±0.2	-1.3±0.1	-0.6±0.2

RMS OF WEIGHTED RESIDUALS

	263	268	269	270	275
	3.6	1.8	2.2	6.1	1.7

TABLE 9

SIX HOUR DOPPLER SOLUTIONS
SHELL RELATIVE TO NSWC

CASE A-FREQUENCY PARAMETERS PER SOLUTION

DAY	263	268	269	270	275	276
FREQUENCY SOLUTIONS-LAST PASS (NS/DAY)						
SAT5	721±56	783±54	1048±52	-49±62	618±53	-329±223
SAT6	-649±66	-352±169	-2124±94	-647±111	-860±65	-269±191
SAT8	427±126	-61±115	-1299±161	785±153	-691±153	11±120
SAT9	-4804±177	-716±73	-2152±51	2307±156	-101±169	539±181
SHELL	-403±1	-264±1	-283±1	-214±1	-261±1	-4±14
NSWC COORDINATES (M)						
HEIGHT	-8.1±1.9	-18.6±2.7	-45.7±1.9	87.8±2.9	5.4±1.9	-12.8±4.3
EAST	14.8 1.6	-23.0 2.7	21.8 2.2	-45.3 2.5	-29.9 1.8	-19.1 4.9
NORTH	-6.2±1.9	-7.2±1.9	-15.3±1.9	34.2±2.1	-4.1±1.9	8.3±3.8
SHELL COORDINATES RELAITVE TO NSWC (M)						
HEIGHT	-1.9±.05	-0.5±.10	-2.0±.05	-2.8±.05	0.8±.10	-0.1±.12
EAST	1.8±.03	0.9±.05	0.7±.04	-1.5±.04	1.4±.04	0.1±.28
NORTH	-0.8±.02	-0.3±.03	0.0±.02	0.9±.04	-0.1±.03	0.1±.50
RMS OF WEIGHTED RESIDUALS						
	8.2	3.0	2.7	9.2	2.1	1.0

TABLE 10

ORBIT CORRECTIONS FROM CASE A
SHELL/NSWC SOLUTIONS

DAY	263	268	269	270	275	276
SINE COEFFICIENTS (M)						
RADIAL						
SAT5	17±2	-33±3	-37±3	18±3	-19±3	-5±4
SAT6	-1±3	-11±4	16±3	-11±4	-15±3	16±4
SAT8	19±3	3±3	20±4	-58±4	4±4	30±4
SAT9	49±4	6±3	9±2	122±4	2±5	10±5
TANGENTIAL						
SAT5	88±7	91±7	10±6	36±8	108±7	-44±10
SAT6	80±5	30±8	12±8	102±8	27±5	-10±9
SAT8	-1±6	3±6	-30±8	56±8	20±6	51±8
SAT9	210±8	25±8	-61±6	129±8	11±8	54±8
NORMAL						
SAT5	-144±4	-60±6	10±4	13±7	-73±5	54±15
SAT6	212±8	31±11	-39±10	116±10	22±7	-45±14
SAT8	55±12	44±8	48±14	-28±13	149±12	49±8
SAT9	-20±11	5±10	-74±9	416±10	-4±11	-25±11
COSINE COEFFICIENTS (M)						
RADIAL						
SAT5	21±3	19±3	-23±3	59±3	17±3	74±5
SAT6	21±2	-18±4	25±3	-7±2	13±2	-2±5
SAT8	0±4	-16±4	3±4	-19±4	4±4	-21±4
SAT9	-8±4	24±3	26±2	-155±4	-2±4	-5±4
TANGENTIAL						
SAT5	23±7	11±8	121±7	-38±8	-10±7	-39±10
SAT6	32±7	7±9	-8±8	-19±8	39±7	29±9
SAT8	3±7	23±7	13±8	-113±8	-39±0	44±8
SAT9	56±8	31±8	14±8	-180±8	4±8	15±9
NORMAL						
SAT5	-2±6	-50±6	-105±6	124±6	19±5	16±15
SAT6	-83±6	-74±12	54±10	107±11	-17±7	-21±12
SAT8	-1±8	11±9	5±12	52±12	157±12	-4±9
SAT9	-253±13	80±11	180±9	-131±10	11±12	86±11

TABLE 11

SIX HOUR DOPPLER SOLUTIONS
SHELL RELATIVE TO NSWC

CASE B-FREQUENCY PARAMETERS EACH PASS

DAY	263	268	269	270	275	276
FREQUENCY SOLUTIONS-LAST PASS (NS/DAY)						
SAT5 ±		-15±98	389±76	530±83	498±56	-404±220
SAT6 ±		-681±173	-1690±129	-3024±128	-320±96	-113±141
SAT8 ±		75±119	-896±162	-592±154	969±161	-173±160
SAT9 ±		-1843±142	-1456±114	4484±111	-139±146	542±182
SHELL ±		-275±12	-293±7	-80±7	-61±89	-25±51
NSWC COORDINATES (M)						
HEIGHT	-28.6±2.0	-7.9±3.2	-38.0±2.2	-24.3±3.0	-5.2±2.1	-10.1±4.5
EAST	41.6±2.1	-40.6±3.0	17.7±2.5	-5.9±3.0	-1.1±2.5	-22.7±4.7
NORTH	-21.8±1.9	4.3±2.3	3.0±2.3	20.5±2.3	9.1±2.0	9.1±3.9
SHELL COORDINATES RELATIVE TO NSWC (M)						
HEIGHT	-6.8±0.2	-0.1±0.3	-2.8±0.1	-6.5±0.2	0.4±0.4	-0.5±1.2
EAST	3.2±0.1	-2.0±0.2	-2.0±0.1	0.7±0.2	0.1±0.3	-0.4±1.4
NORTH	-0.9±0.1	2.2±0.2	-0.6±0.2	-0.3±0.1	-2.0±0.2	0.2±0.8
RMS OF WEIGHTED RESIDUALS						
	6.9	2.1	2.5	3.2	1.6	1.0

TABLE 12

SIX HOUR DOPPLER SOLUTIONS
SHELL RELATIVE TO NSWC

CASE C-FREQUENCY PARAMETER MAX. SPAN=60 MIN.

DAY	263	268	269	270	275	276
FREQUENCY SOLUTIONS-LAST PASS (NS/DAY)						
SAT5	241±56	259±65	116±77	-327±105	427±57	-365±220
SAT6	-135±92	-996±174	-1841±131	42±131	-345±98	-220±164
SAT8	408±117	-205±110	-747±151	1203±141	550±145	8±106
SAT9	-4597±179	-3±128	-1576±109	3506±139	55±157	532±182
SHELL	193±17	-287±12	-345±13	-287±15	-183±80	-29±51
NSWC COORDINATES (M)						
HEIGHT	-0.1±2.0	-33.2±3.0	-20.6±2.2	123.2±3.0	-5.8±2.1	-12.1±4.3
EAST	13.8±2.6	-31.8±3.0	-11.1±2.7	-55.2±3.1	-2.7±2.7	-20.7±4.6
NORTH	-6.8±2.0	13.9±2.4	-3.8±2.3	37.0±2.3	2.3±2.0	7.7±3.9
SHELL COORDINATES RELATIVE TO NSWC (M)						
HEIGHT	-1.1±0.4	-2.3±0.3	3.4±0.4	-1.3±0.5	-0.7±0.4	-0.7±1.2
EAST	-5.4±0.4	-5.2±0.4	-7.8±0.4	1.2±0.5	-1.2±0.4	-0.3±1.5
NORTH	0.1±0.2	0.6±0.2	1.1±0.2	3.8±0.2	1.0±0 2	0.2±0.8
RMS OF WEIGHTED RESIDUALS						
	7.2	1.9	1.8	8.2	1.5	1.0

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